Trabajo de Fin de Grado

Titulación

Grado Ingeniería en Tecnologías Industriales

Technical-economic analysis of Gas Insulated Lines

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Convocatoria: Julio 2018

ETSEIB

Abstract

The increasing electric demand shows the need of a grid reinforcement which is going to be accomplished in the following years. These new lines will have to be designed focusing on efficiency and sustainability in order to improve the performance of the power grid. These new parameters give us the opportunity to talk about Gas Insulated Lines (GIL) due to its low transmission losses, and high transmission capacity [1].

This project presents a technical-economic analysis for GIL, to approximate the total cost of a GIL infrastructure with its singular technical arrangements, both initial investment costs and long term costs due to the operation. To accomplish it all cost components have been approached as function of nominal values of a GIL project; for this reason a study has been done for each single cost component to relate the technical solution with costs.

A number of parameters (such as geometric measures, mass of insulator gas, conductor resistance, capacitance or inductance) of the installation have been obtained by statistic regressions based on data from available sources. These parameters have been needed to come up with the installation price.

In addition a case study is presented, where different technologies are compared in terms of cost. The objective is to show differences in the price for each component between the different technology arrangements for the given case. It can be seen that there are significant differences between technologies in the initial inversion cost and the life-long operation cost.

With the case study which is referred to a regular installation, can be seen which is the cheapest electric solution and which is the higher cost efficient technology, which leads to a low price investment and operating expenses.

Content

List of acronyms

OHL	Overhead Lines
GIL	Gas Insulated Lines
GIS	Gas Insulated Switcher
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
UHV	Ultra High Voltage
PTC	Power Transmission Cost
AC	Alternating Current
DC	Direct Current
XLPE	Cross-linked polyethylene

1. Introduction

1.1 Future power supply system

Nowadays the entire world is claiming for a solution to the pollution problems yet visible in many different planet catastrophes. These worries have been come through in the 2015 United Nations Climate Change Conference**,** held in Paris 2015. However the power consumption is increasing, what will have as a consequence the search for new energy sources.

To accomplish EU's target for 20% share of energy from renewable energies [2], some changes must be introduced in the power generation system. It means, renewable energy sources are undoubtedly going to be the future in the electric power market. Normally these sources tend to be far away from the principal load centres and need to be connected with long and wide electric nets. This factor and the increasing electric demand lead to think about an optimized international long-distance high-power transmission network.

Nowadays in the European Union there are weak international connections, which are working in case of power mismatch between production and demand. In order to reinforce the percentage of renewable electric consumption, a large scale ultra-high voltage (UHV) for Alternating Current (AC) or Direct Current (DC) system must be inserted. This long transmission system is motivated by the need of taking profit of renewable energy independently where it is produced. As an example, great renewable energy sources are located in the northern seas in Europe for wind power production.

Reliable cross border connections are needed to boost not only the integration of renewable energies, but also to ensure security in energy supply. For these reasons countries in European Union must have by 2020 at least a 10% of total power capacity interconnection with other countries [3].

In conclusion, High Voltage Alternating Current (HVAC) long-distance transmission systems are needed to ensure security and reliability in the future international grid. Besides it is taking great importance the concept of net efficiency which brings us to the study of Gas Insulate Lines (GIL) because of its low transmission losses and low capacitive and inductive compensation needs [4].

1.2 Overhead lines, Underground Cables and Gas Insulated Lines (GIL)

An introduction to Overhead Lines (OHL) and Underground Cables and GIL is done in order to compare OHL and Underground Cables with GIL in terms of total costs in a case study done in chapter 4.

1.2.1 Overhead lines

Nowadays OHL is the most commonly used system for UHV AC connections between power stations and big consumers; to date, they are the most cost-effective method of HVAC transmission [5]. An OHL route consists of conductors in form of cables hanging from towers. The route design is a balance between the size and distance of the structure towers [5]. Also this decision is taken into account with the considerations of other aspects as visual and environmental impact. In Spain the OHL transmission grid (UHV network) works between 220 and 400 kV and has a total distance of more than 40.000 km.

In Figure 1 an OHL tower is shown. The main characteristics of the installation shown in this picture are: it has got two circuits with three-four conductors per phase; conductors of the same circuit and the same phase form a beam; conductors of different phases are separated at stipulated distances to avoid electric hazard; conductors forming a beam are separated between them with insulators, as well as conductors with the tower.

In Figure 1 is shown a typical OHL tower, it is the same one as used in the case study.

Figure 1. OHL tower. (Data source: [6])

1.2.2 Underground cables

Underground cables are used across the world along with OHLs. The main reason for using this system is for OHL space and environmental restrictions, for example environmental protected areas or high density populated areas.

Unlike OHL, underground cables cannot use air as the insulating medium; as air can transfer heat from the conductor away much better than cables with cable insulation. Therefore, larger cables are needed to transmit the same power as OHL. The probability of using reactive compensation units is related to operation voltage, conductor size and circuit length; it is important to remark that cables do have higher inductance and capacitance rates.

In Figure 2 it can be seen a normal round tunnel with three cables corresponding perhaps to different phases.

Figure 2 Underground cable tunnel. (Data source: [13])

1.2.3 GIL

Gas Insulated lines are the safe alternative to overhead lines. The low impact on the landscape and the high transmission capacity make GIL a suitable transmission system to face future grid reinforcements. Perhaps it is the price the first disadvantage in front of other transmission systems; however developments on the field can carry cost reductions.

GIL system can handle large amounts of power, even more than Overhead Lines (OHL), due to its bigger conductor area. The voltage range for GIL covers high voltages from 100kV to 800kV, rates where most of UHV lines work on. As the area is inversely proportional to the resistance[7], the transmission losses of GIL are much lower than overhead transmission lines. GIL is the best option for high voltages due to high power rating.

The GIL concept was firstly developed in the 1960s, it is known as the GIL 1st generation, which worked only with SF_6. Further investigation and tests did prove that mixing SF_6 and N_2 (GIL 2nd generation) would reduce installation costs and gas handling difficulty.

Since 1970 more than 150 GIL projects have been installed worldwide, all of them proving its outstanding performance capability [8]. GIL installation can be done in dedicated trenches, above-ground or in tunnels. Also, there is the possibility of installing GIL lines in sharing structures such as railway tunnels, highway networks or even gas lines.

Nowadays GIL are based on $\mathrm{N_2}$ + $\mathrm{SF_6}$ tubular conductor technology. As it can be seen in Figure 3, it consists of a central aluminium conductor with a typical electrical cross section of up to 5300 $\mathrm{mm^2}$ [9], inside an outer enclosure pipe. The conductor lies on the centre of the outer enclosure, resting on cast resin insulators. The enclosure provides a solid mechanical and electrical containment for the system. The fully encapsulated enclosure protects GIL against outside influences and provides a free maintenance system. The space between the outer enclosure and the conductor is filled with the gas mixture ($\mathrm{N_2}$ + $\mathrm{SF_6}$) which nowadays this mixture is around 20% $\mathrm{SF_6}$ and 80% $\mathrm{N_2}$. This mixture has been since many years tested to prove its insulation reliability.

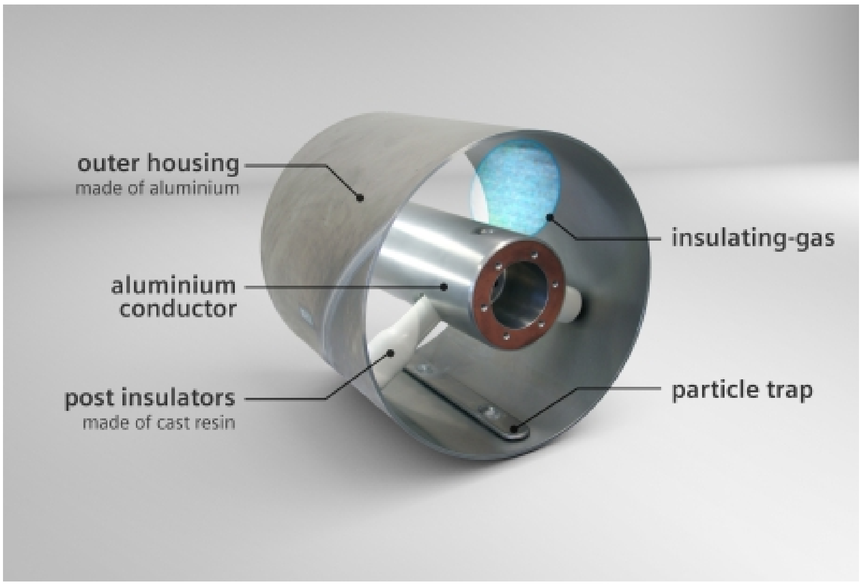

Figure 3 GIL layout. (Data source: [4])

The high security that GIL is able to offer differentiates GIL from other transmission systems which expose the grid effectivity to some climate hazard. The current gas mixture used gives very good electrical insulation properties, which enable flexible route planning. In addition, this mixture is non-toxic, inert, non-flammable, non-corrosive and long-time stable. However, $\mathrm{SF_6}$ is a greenhouse gas which may be highly harmful for the environment, this is the main reason for doing further investigation on alternative gases.

At the end of its life cycle, all materials and the gas mixture being used can be 100% recycled.

Some typical technical data of GIL is shown in Table 1 [10]:

Table 1. Typical data of GIL installations. (Data source [6]).

Gas insulated transmission lines - technical data parameters	
Rated voltage	100-800 kV
Rated current	Up to 4500 A
Rated short circuit current	63 kA/3s
Rated transmission load	2200 to 3900MVA
Insulating gas	20% N_2 + 80% SF_6
Capacitance	55 nF/km
Resistance	6-8 mΩ/km
Inductance	220 nH/m
Outer diameter	375 to 500 mm
Weight per phase	50 kg/m

1.3 Interest of Gas Insulated Lines

Power transmission for UHV systems both AC and DC is normally done by overhead lines (OHL). This method is not always suitable in relation to electromagnetic field restrictions, especially in very populated areas; also there is a huge interest in the looking up for new energy transmission systems with lower power losses and reactive power generation or consumption. That encourage us to look up for other transmission systems as GIL unlike actual OHL has got higher long-distance transmission efficiency rates in relation to the lower transmission losses, and lower capacitive load.

Some notorious advantages of GIL for high power transmission:

- Low transmission losses: resistive losses are low because of the large cross-section of the conductor and enclosure pipes.
- Low capacitive load: electric phase-angle compensation is only needed at very long lengths because the low capacity of GIL. This implies no further expenses, and higher quality offering.
- High safety: no fire and explosion hazard. Unlike other systems, GIL, are safe to touch in operation, as their enclosure is solidly grounded.
- High reliability: based on the experience from previous projects, failure is very unlikely to occur.

- No electric and thermal ageing: gas insulation does not age due to the low thermal and magnetic rates which are widely lower than the maximum working conditions.
- Electromagnetic fields: this is one of the most important advantages for using this technology as international limitations are getting highly restrictive with electromagnetic fields, especially in very populated areas. GIL result in much smaller electromagnetic fields as the low electric impedance of the outer enclosure pipe allows an induced current which is shifted with current flowing through the conductor. The result of the addition of both electromagnetic fields, is a reduction of total electromagnetic field by at least 95% [11].

GIL can be seen as an alternative to overhead lines, when these cannot be built because of electromagnetic or environmental restrictions. They would be of high interest if apart from having important advantages in comparison with overhead and underground lines, were also worth for their lower total cost of ownership.

1.4 Objectives

This project focuses on giving a cost estimation for each technologic GIL solution, and to prove whether GIL transmission systems are suitable for economic requirements. Once we have a cost estimation for GIL, an approach of the total cost for different transmission systems (GIL, OHL and Underground Cables) is done for a case study in order to know cost differences and see whether GIL is advantageous in front of the others.
The main objectives underlying this matter are:

- Develop a cost calculation tool for Gas Insulated Lines GIL, which can give governments and companies a budgeting for the initial installation of different size ultra-high voltage lines. This budgeting is obtained as function of different variables (transmission length, rated power, voltage level, etc.).
- Provide an economic study of life-long costs related to operation, maintenance, and total active power reduction caused by power losses and reactive power generation or consumption of the lines. All these expenses are obtained as function of different variables (transmission length, rated power, voltage level, etc.).
- Do an economic comparison between OHL, Underground Cables and a GIL installation for a given case. Prove if it is the case that total cost of a given GIL infrastructure are lower than by using OHL or Underground lines. Note which are the differences of cost of the components of each type of transmission system.

The thesis is divided in the following chapters:

- **In Chapter 2: GIL technical background and part description**. The objective is to give an introduction to the technique of GIL and to realize which are those technical parts that compound the total cost of the infrastructure.
- **In Chapter 3: Cost modelling**. The objective is to do a cost approximation of the GIL infrastructure in dependence on some base parameters of each installation.
- **In Chapter 4: Case study**. The objective is to do a complete case study of a given line and see total costs of different technologies. A sensitivity study for the GIL technology is done to know how varies cost in reference to some material's price variation. Also, the objective is to come to the conclusion of which is the most suitable system for the studied case. That is, there is the aim to see whether GIL has got lower total costs than other technologies and to discuss the differences in cost of the components of the different techniques.
- **In Chapter 5: Conclusion**. The objective is to come to the conclusion of which is the most suitable system for the studied case. Also there is the aim to see whether GIL has got lower total costs than other technologies and to discuss to differences in cost of the components of the different techniques.

2. GIL technical background and part description

2.1 Description of GIL technology components

Gas-insulated system of GIL is made of support insulators, conductor and aluminium enclosure and the insulating gas. The principal design criteria for GIL is a cylindrical conductor pipe and enclosure.

2.1.1 Insulation Gas

In the 1960s the first experimental tests were done using SF_6 in high-voltage conditions both with AC and DC voltages. It was seen that this gas was the best solution for high electric power transmission, due to the good insulating capacity and the excellent arc-interruption capability. DC did cause many problems to dielectric stability of the insulating system, therefore, GIL investigation and development focused only in AC transmission[11].

The SF_6 is an artificial gas which is non-toxic, non-flammable, non-corrosive, inert and stable in time. Furthermore, SF_6 gives a high arc-extinction and high insulation capability, as reduces the dimensions of high voltage enclosure. In terms of environmental impact, SF_6 has a high global warming potential, what requires a closed-loop control of the gas. Some further investigation on gas alternatives to SF_6 for UHV applications have come out with CF_3I which is a proven and soon will be a ready-to-go alternative insulating gas mixture [12].

2.1.1.1 First GIL Generation

Firstly used in 1960, the First GIL Generation was using only SF_6 as the insulating gas due to its high insulating capability. Although it gave excellent results providing high transmission reliability, capability and security, for the following reasons further investigation on insulating gases with similar characteristics was done:

- SF_6 artificial gas is expensive compared to gases as N_2 [11].
- SF_6 gas has a high global warming potential. It is 23000 times higher than CO2.[10]

Future necessities, environment concern and regulation in power transmission led to further investigation due to the necessity of obtaining other cheap alternatives to OHL.

2.1.1.2 Second GIL Generation

The second GIL generation differs from the first one that in this case the insulating gases are a mixture of 20% SF_6 and 80%N_2. The need for a competitive price for GIL to hold it as an alternative to other transmission systems and the great impact that SF_6 can have to the environment are the main reasons for this Second GIL Generation.

It was in 1994 when the Second Generation was designed. Mixing SF_6 with N_2 provides also a good insulation capacity. In order to maintain similar insulating rates to GIL First Generation, the pressure may be increased for the 20% SF_6 and 80%N_2 gas mixture [11].

Dielectric properties of the gas mixture are related to gas density inside the enclosure. Gas density, is related to temperature and pressure. Therefore, gas density is monitored by a continuous measuring system, to ensure constant safe operation.

2.1.2 Conductor and enclosure set-up

The conductors' and enclosure's set-up dimensions differ between different voltage rates, gas pressure, and the rated current. In Figure 4 can be seen the principal parts of a GIL unit.

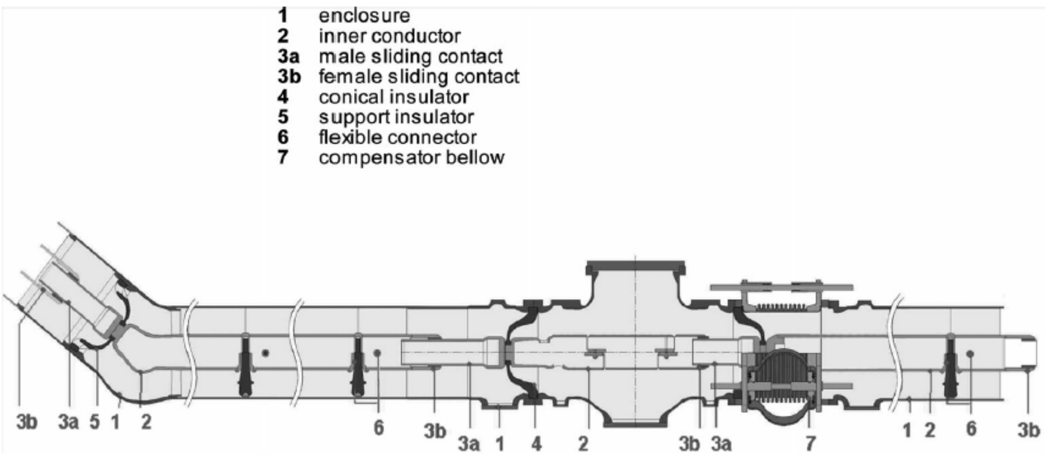

Figure 4. Conductor and enclosure set-up. (Data source: [9]).

In the following sections the main parts of a GIL set-up are described in detail.

2.1.2.1 Enclosure

The enclosure pipe is normally made of aluminium sheets which are normally produced by pipe extrusion. The required thickness of this pipe is important to ensure pipe's mechanical resistance, but also to allow the possibility of elastic bending with a maximum 400 m radius [13].

Due to transportation requirements, pipes are joined together by welded joints, at distances of around 12-15 m [11]. The jointing process is done by welded arc; this welding machine has an ultrasonic sensor system which tests the weld to avoid porosities and give a checking of the quality of the weld.

2.1.2.2 Conductor

The conductor pipe is an extruded pipe of electrical aluminium with high electric conductivity. The same problem as the outer enclosure pipe have the conductors as their length is bounded to around 12-15 m by the transportation length capacity. A similar method for welding the outer enclosure pipes is used for the conductors' joints. The surface of the conductor welded joints must be of very low roughness (10-20 µm) to fulfil high-voltage requirements [11]. Finally, the conductor is held by insulators concentrically in the centre of the outer enclosure.

2.1.2.3 Male and female sliding contact and Compensator units

Longitudinal thermal expansion of the conductor pipe is adjusted by the sliding contact system (male and female sliding contact). Each set situated at distances about 100 m [11], eliminates any possible damaging consequences of thermal expansion. Furthermore the multicontact sliding systems allow constant current flow through the contact between male and female.
Regarding compensator units, they compensate the thermal expansion of the outer enclosure. The compensation is made by bellows which are situated in distances of 300 m to 400 m [11]. In case of buried GIL no compensator bellow is needed as the soil weight fixes the enclosure and there is no movement. Notice that in Figure 5 a compensator unit for the outer enclosure and a male and female unit is shown for the conductor's and outer enclosure's thermal expansion.

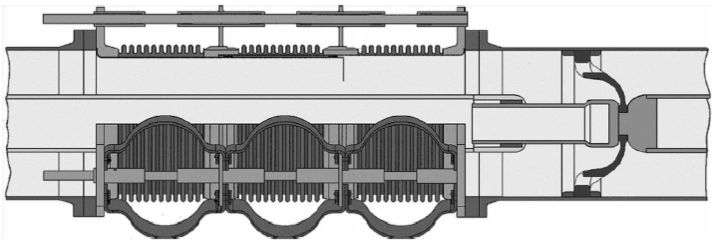

Figure 5. Compensator unit. (Data source: [9])

2.1.2.4 Conical and support insulators

Conical and support insulators made of epoxy cast resin have been developed to fix the inner conductor to the enclosure and to separate the gas compartments. They must give the proper mechanical and temperature resistance as well as the discharge tracking withstandability.

2.1.2.5 Straight unit

In reference to the different parts indicated in Figure 4, the enclosure (1), where the inner conductor (2) is fixed by conical insulators (4) and on support insulators (5). The longitudinal thermal expansion of the conductor is adjusted by the sliding contact system (3a male sliding contact, 3b female sliding contact). A straight unit has a length up to 120 m made by different joined sections (each section of 12-18 m length) welded together by an orbital welding machine [11]. The straight unit only has an insulator positioned inside the enclosure pipe (one each 120 m); see Figure 6.

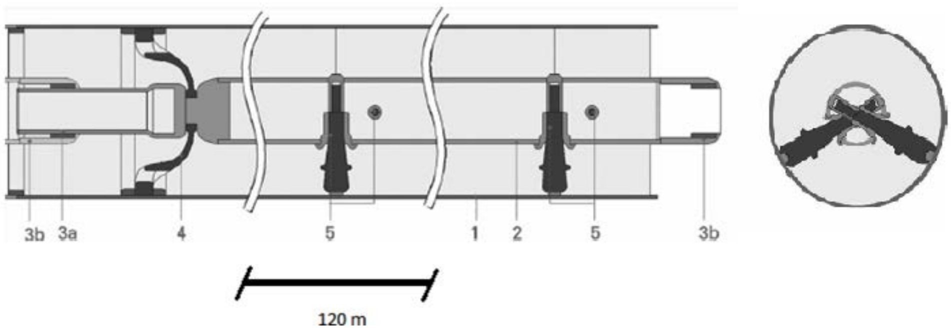

Figure 6. Straight unit. (Data source: [9])

2.1.2.6 Angle unit

The bending radius is a basic project planning parameter to design the routing and total length of the GIL installation. Angle units are designed between 0-90˚. Due to their costs angle units

are only used when smaller than 400 m radius are needed. Under most conditions of landscape, no angle units are needed, because the elastic bending is enough to follow the contour.
An angle unit consists of a single-phase enclosure made of cast aluminium alloy. In the enclosure (1) the inner conductor (2) is fixed by a conical insulator (4) and on support insulators (5). Angle unit is connected to straight unit by orbital welding. In Figure 7 is shown a typical angle unit

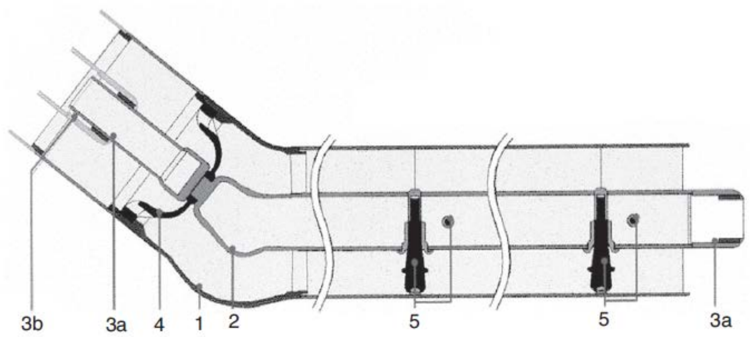

Figure 7. Angle unit. (Data source [9])

2.1.2.7 Disconnecting unit

Disconnecting units used in underground shafts to separate gas compartments and to connect high-voltage testing equipment for the commissioning of GIL. In case it is required to connect gas compartments before and after the disconnecting unit, a bypass can be set. Disconnecting units are located at distances of 1000 to 1500 m. In Figure 8 is
shown a disconnecting unit.

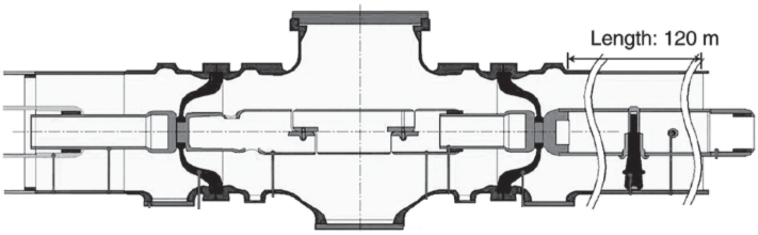

Figure 8. Disconnecting unit. (Data source: [9])

2.2 GIL laying options

Different laying options define different costs, therefore it is important to get to know the main differences between each laying option and even to look for alternatives, such as sharing structures.

Due to GIL significant properties, GIL have been set in many different layouts, to solve complex routing. GIL have been installed in straight vertical, around buildings above and belowground, and even serpentine routings without angle units.

2.2.1 Above-ground installation

Today, more than 50% [11] of GIL installation are solved by using above-ground infrastructure. Costs for this laying system are lower than other options because there are less installation requirements. Furthermore, in this case visual inspections are easily done.

This laying option needs a steel structure to fix it on ground; this structure is in normal conditions situated between 100-120 [11] m distance. Some thermal conditions must be considered when designing the structure; for example in cold countries where snow or ice can come to be an additional load or even wind which causes bending forces.

The type of holding structures can depend on some restrictions which vary the distance to floor. Laying close to ground needs smallest and simpler steel structures; but laying high above-ground (such as 5-8 m height [11]) allows traffic below the GIL but needs of more complex steel structures. These steel structures are then fixed to ground with concrete sockets. In Figure 9 are shown typical steel structures.

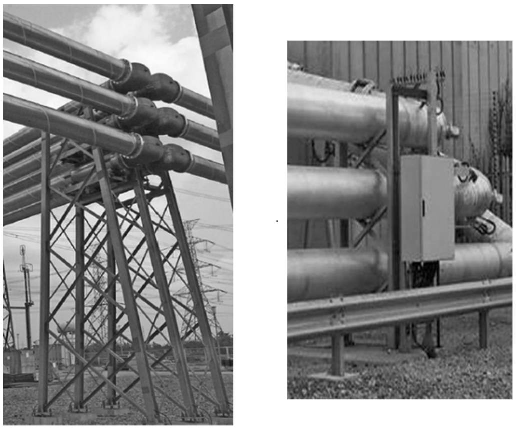

Figure 9.Typical steel structures. (Data source: [9])

As the enclosure aluminium is exposed to air, the oxygen creates an oxide layer, which avoids corrosion. Only water after much time of constant exposure, can corrode aluminium, as it begins a reaction that is able to destroy aluminium self-protection. To avoid this unwanted impact, protection is needed by coating those areas of water penetration. For this coating an external HDPE pipe is used.

It is demonstrated that price for the High Density Polyethylene HDPE coating is negligible as a 400 KV GIL has more than 40 kg/m of metal [13]. From the same reference, the plastic coating pipes weight 9 kg/m [13]. Price of plastic is much lower than price of metal; also plastic protection is only needed for those areas where there is constant exposition to water. For this reason the use of plastic coating won't be accounted in the total cost of the installation.

2.2.2 Trench-laid

The reasons for the use of trench-laid installations are normally when crossing other installations in a power plant. It is a feasible solution when above-ground solutions are not possible. The laying structures of trench-laid GIL are very similar to the above-ground installations as both suffer the same mechanical stress. Therefore, steel structure distances are the same.

Trenches are usually made of prefabricated concrete panels, where the steel structure fixes the GIL. Although being more expensive than above-ground installations, are still very accessible and visual control can be properly done. In Figure 10 is shown a trench laid system.

Figure 10. Trench laid system. (Data source: [9])

In trenches layout, the same aspects about corrosion must be taken into account. The trench needs a trustful drainage and dewatering system to avoid constant contact of water to the enclosure pipe. In case it cannot be assured, painting is needed and control and maintenance are required.

2.2.3 Tunnel-laid

Tunnel laid installation, although being the most expensive laying system, they give the opportunity to set a non-visible from above and accessible power transmission system. Besides, no corrosion protection is needed if it can be ensured that no water can penetrate into the tunnel. This laying system is mainly used when the directly buried laying is not possible.

Tunnel costs depend much on the way they are built: from close-to-the -surface tunnels, water tight, to deep-underground tunnels. In each case a singular study must be done to optimize project costs. Nowadays prefabricated structural elements are reducing construction duration and construction costs.

- Open Trench-Laid Tunnel (squared tunnel section) is the suitable option when close-to-the-surface tunnels can be built. In this case a trench is opened from the ground and tunnel concrete segments, which can be prefabricated or produced on-site, are assembled. Finally, they are covered with soil (minimum covering height 1 m). The GIL systems lies in a small space of 2,5 m^2 for two GIL systems, which leaves enough space for a walkway in the centre of 0,8 m wide. In Figure 11 can be seen a normal section and distribution for a squared tunnel.

Figure 11. Open trench-laid tunnel. (Data source: [9])

- The Bored Tunnels are round and usually have a diameter of 3-4 m for two GIL systems. Highly automatized machines can dig underground to construct bored tunnels; high development in this Bored Tunnels does provide higher speed, accuracy and lower costs (still being very high).

In tunnel-laid installation GIL lays fixed to the tunnel walls. The laying forces are similar to above-ground installations. In both cases steel structures hold the straight unit laid on sliding fixing points to allow thermal expansion of the enclosure. The laying structures of tunnel-laid GIL are situated normally at distances of 28 m.

2.2.4 Directly buried

The directly buried laying system for GIL is getting higher importance in GIL for underground power transmission. This is the power transmission option for long-distance applications, preferably for open landscape across the country; it offers an economical and fast laying solution. In Figure 12 is shown a typical three phase Directly Buried layout.

The laying methods are adapted to oil and gas pipeline laying techniques, as they have been for long proved in long-distance supply of energy:

- When the GIL installation is directly buried into the soil, the outer enclosure needs an outer passive corrosion protection made of polyethylene or polypropylene coatings. The joint area, produced by an orbital welding jointing machine, has a special coating to protect the weld. For the same reason explained in chapter 2.2.1, their price is not accounted in the cost study.
- The surrounding soil needs to be free of stones, to prevent GIL pipe from being damaged; the minimum coverage soil is 1 m. The backfill material is typically a sand and clay mixture so as to keep water in the soil to improve heat conductivity. Normally backfill materials are used after filtering them of rocks and stones. In the areas where GIL has been laid no digging executions can't be done. Furthermore, no tall trees can be planted.
- In order to get this minimum height (1 m) for a single-phase and three-phase GIL a 2-2,5 m depth trench is dug. In case of three-phase electrical transmission, the distance between the enclosure pipes is 0,5-0,8 m. This distance depends on thermal and accessibility affairs. The expected width for a three-phase GIL is 4,5-5 m. All this figures have been given for a 500 mm enclosure pipe diameter. In Figure 12 a typical layout can be seen; the rates indicated in Figure 10 may vary due to differences in technical arrangements.
- In this laying method the straight units do not have to be fixed in the ground to avoid longitudinal movement; in the soil the GIL is anchored due to its weight, so no additional compensation elements are needed.
- Disconnecting units are placed in concrete shafts. The disconnecting units allow access to GIL; in these shafts measurement sensors such as pressure monitoring are located, to control GIL working conditions. As it is indicated in the Disconnecting Unit section (2.1.2.7), each shaft must be situated each 1000-1500 m.

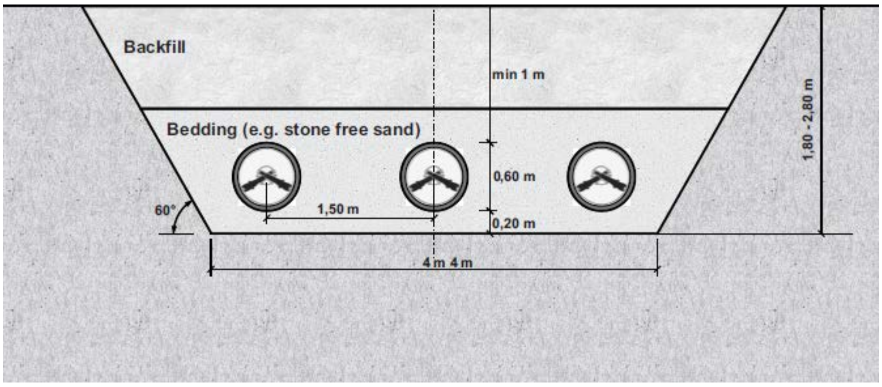

Figure 12. Three-phase directly buried section. (Data source: [12])

In terms of forces, directly buried GIL pipes, have to face the weight of the soil laying on the pipe. That means that at least 1 m height and 0.5 m width section of soil. In addition, in case of having traffic above them or snow, further loads have to be supported by the enclosure pipe.

3. Cost modelling

The main aim of this thesis is to develop a tool for calculating total GIL infrastructure costs, from initial investment to power losses and life-long costs. Note that other associated costs, such as grid reinforcements or insurance costs are out of the scope. In order to simplify calculation it has been disparaged the transient behaviour, and only focused on the stationary state.

This chapter explains firstly how does the tool works, secondly which are the equations that relate the main parameters of the installation with the cost, the technical considerations employed, and functions and variables used to develop the tool.

The methodology used in this economic cost study considers a great variety of asset types, to be able to predict costs of any different layout. That means that the cost is calculated in reference to the type of laying, the routing (number of angle units, etc) and the dimensions of the infrastructure depending on technical parameters. The price of materials used is also a parameter to be introduced in the system to improve the quality of the cost approximation.

GIL systems have got many different technical specifications variables and items that influence greatly in the final cost and make the cost estimation extremely complex. In order to simplify cost calculation, the cost components have been separated into:

1. **Fixed costs related to initial investment**
    - Pipe and conductor
    - Civil works
    - Gas
    - Transport and installation
    - Routing (angle units, disconnecting units)
    - GIS + Transformers + Testing + Reactive power compensation
    - Project contingency
    - Project management

2. **Variable costs**
    - Power losses
    - Cost of reduced power transmission capacity due to reactive power
    - Losses in the compensation unit
    - Operation and maintenance

Finally, in the cost approximation of a three-phase enclosed GIL it has been always studied the case which each phase conductor is inside a different pipe, and not the case which all conductors are inside the same enclosure pipe.

3.1 Tool description

The tool works with the following principles: first, users introduce the main data regarding GIL technology (see chapter 3.2). The tool determines the costs for the entire project returning the total cost and also the cost associated to each component.

An approach to minimize the number of inputs has been done whenever it has been possible. However in the search to be realistic and do an accurate prediction, users, do have to introduce some real information such as current prices of materials used in the infrastructure (metal, gas prices), or some data referred to the infrastructure.

3.2 GIL variables and modelling

Regarding GIL infrastructure cost calculation, many variables are significantly dependent to the final cost. To achieve a model for calculating the final cost, first of all, inputs and variables are needed to provide different scenarios.

The main inputs used in this tool are the nominal voltage in kV and the nominal apparent power; but some other information has to be introduced which is indicated in Table 2.

Table 2. Main variables.

Variable	Unit
Nominal apparent power	**MVa**
Nominal voltage	**kV**
Lifetime	Years
Discount rate	(per unit)
Total length (referring length for type of laying and soil)	m
Cost of MW/h	€/MWh
Single/Three phase	-
Number of parallel units	-
Price Aluminium outer enclosure	€/kg
Price Aluminium conductor	€/kg
Price SF_6	€/kg
Price N_2	€/kg
Number of transformers	-
Number of GIS (Gas insulated switchers)	-

With the nominal voltage (V) and the apparent power (S), intensity (I) per conductor can be calculated. Note that in the (1), (2) V is referred to the phase-to-phase voltage.

- Single phase systems: S_{s-p} = V * I (1)
- Three phase systems S_{t-p}= 3 * $\frac{V}{\sqrt{3}}$ * I (2)

A number of other parameters not specified in Table 2 directly depend on the specified variables used in this tool. When the total length is indicated then the number of disconnecting units, male and female sliding, and compensator units is known. Disconnecting units are situated at distances of 1000-1500 m (in the tool is used 1250 m) to separate gas compartments and connect testing hardware. Male and female sliding contact units are situated each 100 m to cope with thermal expansion. Compensator units are situated at distances of 300-400 m (in the tool is used 350 m) to compensate the thermal expansion of the outer enclosure. In cases of directly buried laying system, no compensator units are needed [11].

In order to approximate costs, a relation between technical variables and cost is obtained as statistical regressions. The criteria chosen to provide a statistical regression, is to minimise the sum of the mean square error (3).

Minimise: $Q(b_0, b_1) = \sum_{i=1}^{n}(Y_i - y_i)^2$ (3)

Where Q is the function to minimise (the sum of all the mean square error); Y_i is a value from the sample population; and y_i is the theoretic value adjusted by a regression. Depending on the regression equation we get different adjustments; the regression equations considered are exponential, linear, logarithmical, polynomial, and potential.

To assess the quality of the regression adjustment; the parameter R^2 is given:

- $0 \leq R^2 \leq 1$

The closer R^2 is from 1 better is the adjustment.

3.3 Cost dependency on transmission capacity and routing

Cost depends clearly on distance; the main part of the installation cost is due to the aluminium pipes for enclosure and conductor. Materials represent around 40% of the initial investment cost [4].

A remarkable part of the installation cost of GIL is for the aluminium pipes, for the outer enclosure and conductor; however, it is remarkable to say that angle units, disconnecting units do contribute on the total cost but do have a smaller share of the materials' cost as they are used only at long distances. On the other hand, the cost for insulators is much lower as they represent less than 0,5 % of total GIL volume, for this reason insulators' price is considered as negligible. [11]

3.3.1 Outer enclosure cost dependency

The material used for the outer enclosure is extruded aluminium; which withstand mechanical forces and high pressure, as well as external forces from the environment, such as wind or snow. Also in order to cope with soil load, aluminium alloys are used to improve the mechanical strength of pure aluminium.

The selected aluminium alloy for the enclosure pipe must be a balance between cost, conductivity and anticorrosion features, also welding has to be possible. The alloy used to obtain costs for this economic study is the aluminium alloy A5052 in the Japan JIS, already used in some GIL projects [14], which in the European Standard EN 573-1-2 is known as 5052 [15].

Despite knowing that the outer enclosure diameter depends on many technical aspects such as mechanical or thermal conditions, in order to find a relation between variables and costs some actual diameters of different projects of GIL around the world are related to voltage.

Outer enclosure diameter for each rated voltage (mm); Table 3 from [11] and Table 4 from [16]:

Table 3. Outer enclosure diameter

Voltage (kV)	72,5	160	270	362	420	550	800	1200
Diameter (mm)	229	343	406	483	610	648	749	889

Table 4. Outer enclosure diameter

Voltage (kV)	160	270	362	480	800	1200
Diameter (mm)	240	310	380	500	630	760

In Figure 13 is shown the statistic regression between enclosure diameter (mm) and rated voltage (kV).

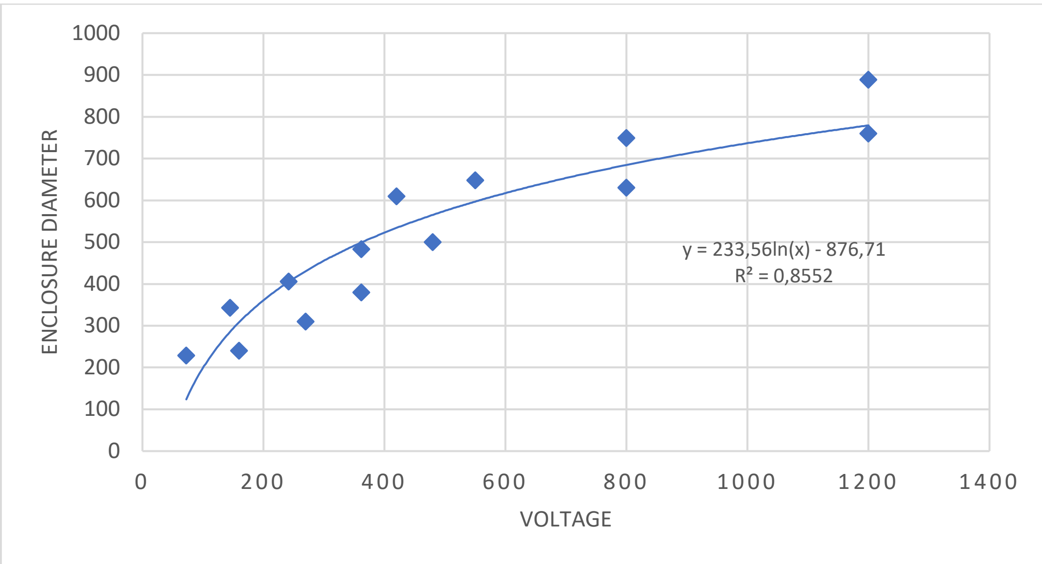

Figure 13. Outer enclosure diameter (mm).

The equation obtained is:

$D = 233{,}56 \ln(V) - 876{,}71$ (4) ($R^2 = 0{,}8552$)

where;

V: phase-to-phase voltage [kV];

D: outer enclosure diameter [mm].

Regarding the wall thickness of the outer enclosure, total cost of the infrastructure depends highly on it. In the trial to give a relationship between constructive parameters and technical aspects, although each single GIL project has a thermal layout to choose the right outer enclosure wall thickness, a regression between voltage and wall thickness is done, using values from different GIL projects from around the world, to be able to give the cost approximation.

The outer enclosure wall thickness mm is shown in Table 5 [3].

Table 5. Outer enclosure wall thickness

Voltage (kV)	160	270	360	460	800	1200
Wall th. (mm)	7,6	7,6	6,4	6,4	6,4	9,5

In Figure 14 is shown the statistic regression between the outer enclosure wall thickness (mm) and the rated voltage.

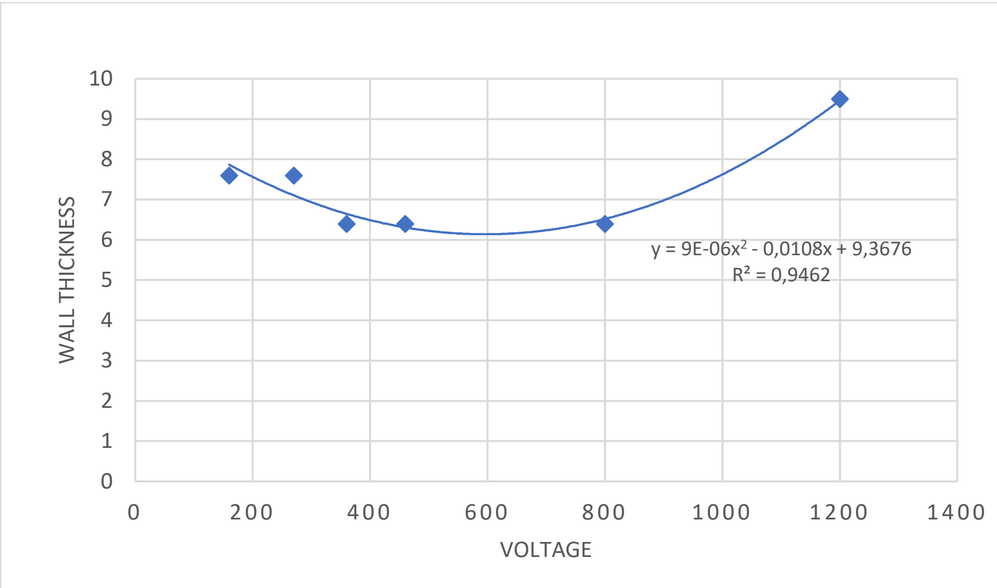

Figure 14. Outer enclosure wall thickness

$TH = 9E-06x2 - 0{,}0108x + 9{,}3676$ (5) ($R^2 = 0{,}9462$)

where;

TH: wall thickness [mm];

V: voltage phase-phase [kV].

In order to come up with the outer enclosure pipe costs, GIL pipes are obtained by the aluminium extrusion process. Price of pipes obtained by this manufacturing process is calculated with the metal prices [17]. The aluminium alloy is AlMg2,5 with a density of 2680 kg/m^3 [18].

The cost of the outer enclosure is calculated with:

$$C_{Outer\ enclosure} = V * \rho * P = \pi * \frac{D^2-(D-2\ TH)^2}{4*10^6} * l * \rho * P \qquad (6)$$

where;

$C_{Outer\ enclosure}$: cost of the outer enclosure [€];

V: volume [m^3];

P: price of the aluminium [€/kg];

l: total length [m];

ρ: density [kg/m^3].

In case of three-phase and parallel GIL systems, the cost of the outer enclosure is multiplied by the number of parallel pipes.

3.3.2 Conductor cost dependency

The conductor is also made from an aluminium alloy and as well as the outer enclosure pipe, the conductor has also a wall thickness. Regarding the design features for deciding the appropriate alloy, we must focus on conductivity and economic aspects. Furthermore it is important knowing that the conductor must withstand electromagnetic forces and heat. The alloy used is known as in the European Standard EN 573-1-2 6063 [14].

Some values for the conductor diameter have been collected from different GIL projects in order to give a statistical relationship between rated voltage and the conductor diameter.

Values for the conductor diameter are shown in Table 6 [19]:

Table 6. Conductor diameter

Voltage (kV)	72,5	145	242	362	420	550	800	1200
Conductor diameter(mm)	51	88,9	101,6	127	152	177,8	177,8	203

In Figure 15 the conductor diameter is expressed in reference to rated voltages.

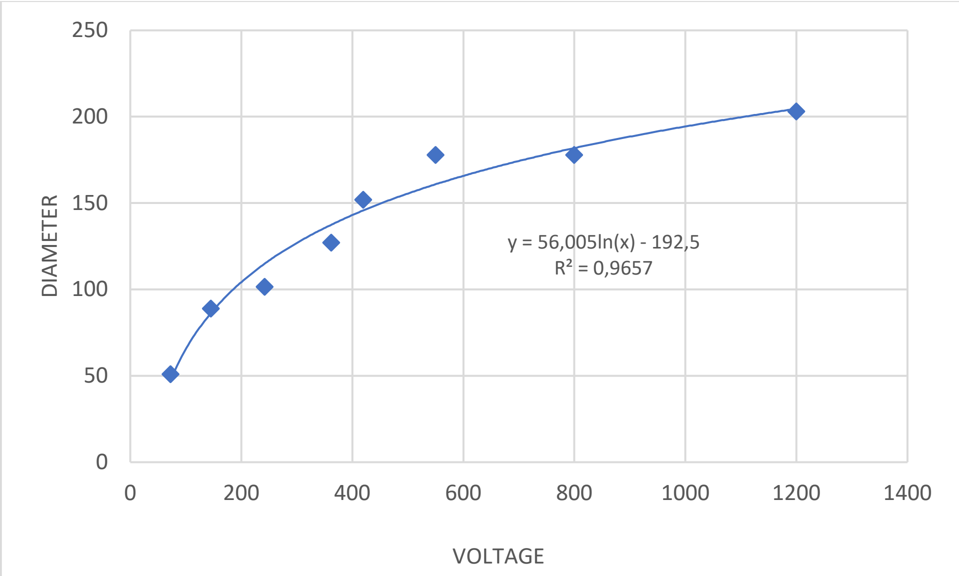

Figure 15. Conductor diameter (mm)

$d = 56{,}005 \ln(V) - 192{,}5$ (7) ($R^2 = 0{,}9657$)

where;

d: conductor diameter (mm);

V: voltage phase-phase (kV).

Values for conductor's wall thickness have also been collected in order to come with the necessary volume and be able to calculate cost related to the conductor [19]. This values are shown in Table 7.

Table 7. Conductor's wall thickness

Voltage (kV)	160	270	360	460	800	1200
Wall th. (mm)	15,2	12,7	12,7	12,7	12,7	12,7

$th = 5E\text{-}06V^2 - 0{,}0087V + 15{,}55$ (8) $R^2 = 0{,}5674$

where;

th: conductor's thickness [mm];

V: voltage phase-phase (kV).

In order to calculate the conductor cost, the same method as for calculating the outer enclosure cost dependency is used [17]. The EN 6063 density is 2690 kg/m^3. [20]

$$C_{Conductor} = V * \rho * P = \pi * \frac{d^2-(d-2\,th)^2}{4*10^6} * l * \rho * P \qquad (9)$$

where;

$C_{conductor}$: Cost of conductor [€].

3.3.3 Disconnecting, compensator units and male and female sliding cost dependency

The cost of these units have been estimated using the Cost Modelling of Solid Works. This cost is then related with voltage with statistic regressions. That is with the mentioned program have been designed each unit with its own measures and then the price for each one has been studied and related to the rated voltage.

In case of angle units, as they depend on route planning they must be specified as a variable ($n_{angle\ units}$). Their total cost is approximated with the following equation:

$$C_{angle\ units} = n_{angle\ units} * 16750e^{0,0016V} \qquad (10) \qquad R^2 = 0,9662$$

where;

$C_{angle\ unit}$: cost of each angle unit [€];

$n_{angle\ units}$: number of angle units;

Disconnecting units as explained in chapter 2.1.2.6 are situated at distances of 1000 to 1500 m. In the cost calculation tool we consider one at 1250 m. Their total cost is approximated with:

$$C_{disconnecting\ units} = n_{disconnecting\ units}(315,48x + 4643,8) \qquad (11) \qquad R^2 = 0,9894$$

where;

$C_{disconnecting\ units}$: cost of disconnecting units;

$n_{disconnecting\ units}$: number of disconnecting units.

In Figure 16 is shown, as an example of the designed pieces done with Solid works, the disconnecting unit.

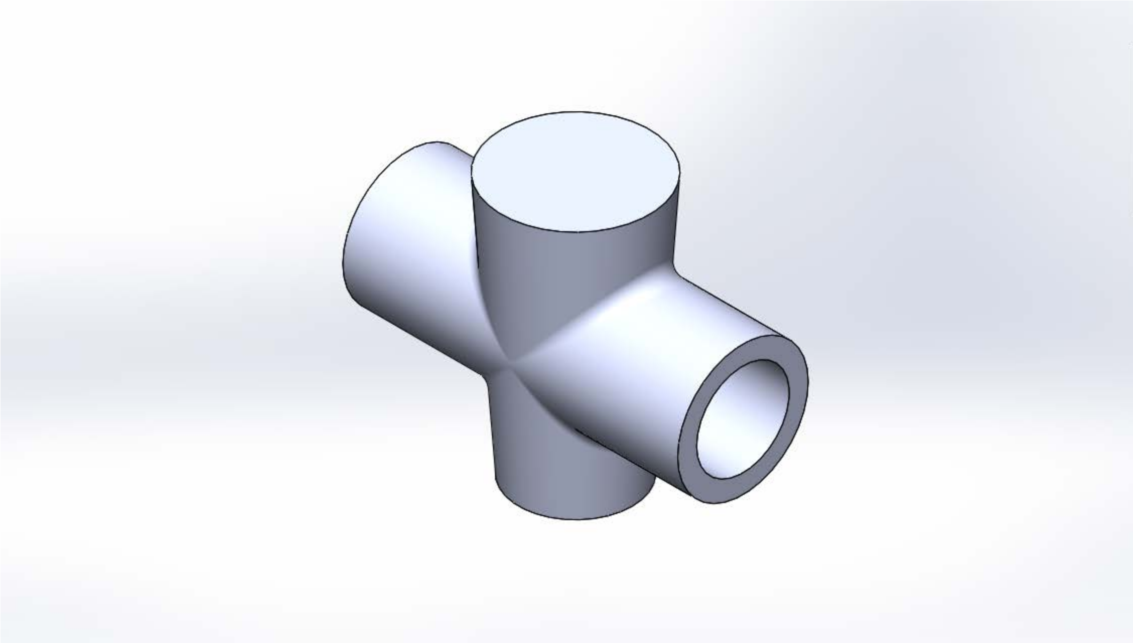

Figure 16. Disconnecting unit, Solid Works design. Source Solid Works.

Note that in case of having more than one pipe, the cost is calculated by multiplying the total number of pipes.

Regarding male and female sliding contact as they are two pipes one inside the other, it has not been considered a special price as no special machining is necessary unlike angle units and disconnecting units.

3.4 Cost dependency on laying methods

Civil work costs for GIL depend much on the site, the laying method and local conditions. Optimising the GIL laying and routing might be significant in the total cost of the infrastructure; for this reason when designing a new transmission line, it is necessary to do a previous research work studying different route planning with their different laying methods and types of soil, therefore, taking into account all the conditionings, to come up with the most suitable solution. This thesis assumes that the route and laying methods are defined previously in each project and that this tool only provides the necessary costs. Note also that the route does influence the total cost for maintenance and other variable costs as power losses.

Regarding the path, standard GIL installations tend to be done close to roads or other communicative systems, as accessibility, maintenance, jointing and welding the pipes is crucial for GIL installation, and for price reduction.

3.4.1 Directly buried laying costs

Directly buried GIL is gaining importance nowadays for undergrounding a GIL infrastructure. This laying method is a continuous process and it can cover long distances much faster than other laying methods like tunnels. Another advantage is that thermal compensation elements are not needed because GIL is held in place by the weight of the soil and friction between the soil and the pipe. Also no steel fixing structure is needed.

The greatest difference with other laying methods is that GIL pipes are exposed to external conditioning with permanent contact with water or humidity, therefore, the aluminium pipe must be bounded to avoid corrosion. Pipes are equipped with a XLPE external protective coating.

Table 8 gives a cost approximation on the cost (€/m^3) for each type of soil excavation. [21]

Table 8. Prices for each type of terrain

Type of terrain	Type of machine	Price(€/m^3)
Disaggregate (a)	Excavator	4,73
Loose (b)	Excavator	5,67
Compact (c)	Excavator	7,09
Hard (d)	Compressor	12,29
Soft rock (e)	Compressor	24,59
Hard rock (f)	Compressor	39,34

Now, in order to calculate costs, it is necessary to estimate the amount of soil that needs to be extracted. In the Figure 17 can be seen the parameters for excavating the trench.

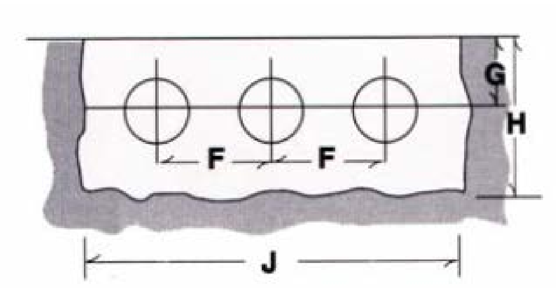

Figure 17. Directly buried section. (Data source: [16])

A regression with each parameter is done to give a relationship between them and the rated voltages installed. Note that parameters J, G, H, F are from a three phase GIL system. Important, in the following equations, V refers to voltage between phase and neutral. Equations are collected at the end.

-**F** [19]

Table 9. Values for F.

Voltage (kV)	145	242	362	420	800	1200
F (m)	0,368	0,457	0,559	0,711	0,813	1,016

-**J** [19]

Table 10. Values for J.

Voltage (kV)	145 kV	242kV	362 kV	420 kV	800 kV	1200 kV
J (m)	1,27	1,5	1,8	2,28	2,64	3,1

-**H** [19]

Table 11. Values for H.

Voltage (kV)	145 kV	242kV	362 kV	420 kV	800 kV	1200 kV
J (m)	1,21	1,2	1,2	1,3	1,5	1,6

-**G** [19]

Table 12. Values for G.

Voltage (kV)	145 kV	242kV	362 kV	420 kV	800 kV	1200 kV
J (m)	0,91	0,91	0,91	0,91	1,07	1,21

Table 13. Statistic regression of the dimensions

	Equation	R^2
F (12)	0,0006V + 0,3464	0,9304
J (13)	0,0017V + 1,207	0,9173
H (14)	0,0004V + 1,1115	0,9420
G (15)	0,0003V + 0,8235	0,9423

Where;

V: voltage phase-phase (kV).

Digging costs are calculated by multiplying total cubic m extracted with digging prices, differencing them between each soil type:

- Single phase systems:

$$C_d = n*J/3*H*\sum_{i=a}^{i=f} d_i * p_i \qquad (16a)$$

- Three phase systems:

$$C_d = n*J*H*\sum_{i=a}^{i=f} d_i * p_i \qquad (16b)$$

where;

J and H: parameters indicated in Figure 17 [m];

d_x: distance of each type of soil [m];

p_i: price of excavating for each type of soil [kg/m^3];

n: number of parallel units.

In order to calculate digging costs for single-phase GIL infrastructure, a simplification is done, the price will be the price for a three-phase system divided by three. In the case of multiple parallel three-phase systems, digging price will be calculated multiplying the number of parallel three-phase systems, with the price for a single one.

3.4.2 Trench laying costs

The trench laying layout is very similar to directly buried but soil extracted is not backfilled. Trenches are made of concrete panels. This laying type is more expensive than above-ground installations, but less expensive than tunnels [11].

In this case unlike directly buried laying, steel structures like tubbing hangers, concrete inserts attachments, etc, are needed to fix the outer enclosure pipe to concrete. They are situated at distances of 100-120 m [22].

Price for all this structural attachments pieces have not been introduced in the calculation tool as they are insignificant among the cost of other components like pipes, but they can be found in [23]. In reference to [24] the steel /iron structures cost is around 1,91 €/kg.

In order to calculate costs, measures for different voltage rates are showed in Figure 18, in order to establish a relationship between them and voltage. As well as it has been explained in unit 3.4.1 (directly buried), the same considerations will be taken for single-phase and for parallel three-phase systems. In addition, a similar formula used to calculate the directly buried laying system costs is used to calculate the digging costs, differentiating the hardness of the soil.

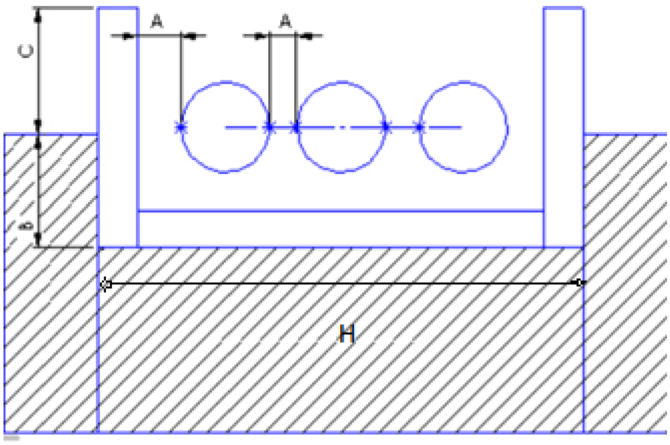

Figure 18. Trench laying section.

Digging costs is expressed as:

$$C_d = B*H*\sum_{i=a}^{i=f} d_i * p_i \qquad (17)$$

where;

- Three phase systems: H= 4A+3D and the normal value for A is 0,3 m.
- Single phase systems: H= 2A+D and the normal value for A is 0,3 m.

B and C: are parameters that depend on each project and are indicated in Figure 18. In the cost calculation tool these values must be introduced as variables.

To calculate the cost of the concrete platforms:

- Single phase system

$$C_{concrete} = p * n * 2d * (B + C) + d * (4A + 3D) \qquad (18a)$$

- Three phase system

$$C_{concrete} = p * n * 2d * (B + C) + d * (2A + D) \qquad (18b)$$

where;

d: distance of the trench [m];

D: enclosure pipe diameter [m]

n: number of parallel units

p: price of concrete panels [$€/\mathrm{m}^2$]

Being price per square meter of the standard concrete panels 17,97 $€/\mathrm{m}^2$ [25]:

3.4.3 Tunnel laying costs

Tunnel laying is normally used when the direct burial installation in trenches is not feasible. Tunnels when laid from the top have a squared form; normally this section is used in rural areas with low population density. For higher density areas round section tunnels are done as they are much deeper than the first ones. Tunnel laying costs are sensitive to route length and tunnel diameter. It is noted that this laying method is the most expensive one.

Dimensions for squared and round tunnels with two parallel GIL systems, are expressed as function of the outer enclosure pipe diameter. The most typical arrangement for the tunnel laying is three phase systems [26].

In the tunnel laying method, fixing steel structures are needed, they are situated each 28 m [11]. As well as it has been done in the trench laying method, the price of this steel structures is not included in the calculation tool as the steel structures may vary in relation to the engineering project; furthermore price can vary between different providers. For example a provider of this structural objects is [23]. The most important reason for not considering their cost is that it is insignificant among the cost of other components of the GIL infrastructure.

As there are three different tunnel options, three different ways for approaching its costs are explained:

3.4.3.1 Squared section tunnels

Tunnels are built in an open trench in segments using prefabricated concrete panels assembled on-site and then covered with soil with a coverage height of 1 to 2 m. To calculate costs it will be considered 1,5 m. GIL is then fixed to the tunnel walls. In Figure 19 is shown two three-phase units in a squared section tunnel.

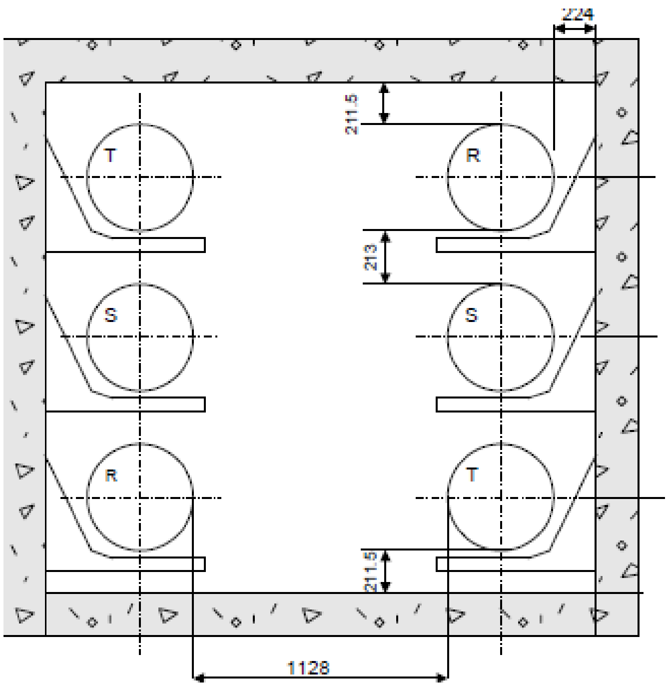

Figure 19. Squared section tunnel. (Data source: [26])

Section S expressed in m^2 for a squared section:

- Tunnel section for two parallel three phase systems:

S= (0,224*2 + 1,128 + 2 *D) * (0,2115*2+2*0,213+3*D) (19a)

- Tunnel section for a three phase system and for single phase system:

S= (0,224*2 + 1,128 + 2 *D) * (0,2115*2+2*0,213+3*D)/1,5 (19b)

where;

D: diameter of the outer enclosure [m].

Cost for squared tunnels is calculated as sum of digging cost and concrete:

1. Cost of digging
   - Two parallel three phase systems:

$$C_d = (S + (0{,}224 * 2 + 1{,}128 + 2 * D) * 1{,}5) * l * p \quad (20a)$$

   - A three phase system or a single phase system:

$$C_d = (S + (0{,}224 * 2 + 1{,}128 + 2 * D) * 1{,}5)/1{,}5 * l * p \quad (20b)$$

where;

C_d: cost of digging [€];

D: diameter of the outer enclosure pipe [m];

l: length [m];

p: price [€/m^3].

Prices for digging for each type of soil are indicated Table 8.

2. Cost of concrete panels:

Being price per square meter is 17,97 €/m^2 [25]:

- Two parallel three phase systems:

$C_{concrete} = [2*(0{,}224*2 + 1{,}128 + 2*D) + 2*(0{,}2115*2 + 2*0{,}213 + 3*D)]*p*l$ (21a)

- A three phase system or a single phase system:

$C_{concrete} = [2*(0{,}224*2 + 1{,}128 + 2*D)/1{,}5 + 2*(0{,}2115*2 + 2*0{,}213 + 3*D)]*p*l$ (21b)

where;

$C_{concrete}$: cost of the concrete panels [€];

D: diameter of the outer enclosure pipe [m];

l: length [m];

p: price [€/m^2].

3.4.3.2 Bored tunnels:

As bored tunnels are deep underground, a shaft is built to introduce the boring machine and the prefabricated concrete segments. In Figure 20 is shown a typical round tunnel section.

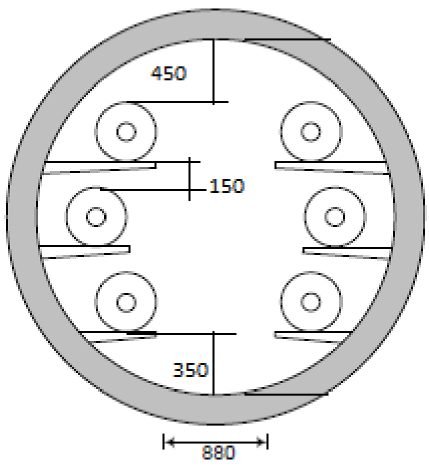

Figure 20. Round section tunnel. (Data source: [13])

The section S for a round tunnel expressed in m^2 for a round section is calculated with the following equations:

- Two parallel three phase systems:

$$S = (0{,}450 + 0{,}150 * 2 + 0{,}350 + 3 * D)^2 * \frac{\pi}{4} \qquad (22a)$$

- A three phase system or a single phase system

$$S = (0{,}450 + 0{,}150 * 2 + 0{,}350 + 3 * D)^2 / 1{,}8 * \frac{\pi}{4} \qquad (22b)$$

where;

D: diameter of the outer enclosure [m].

Notice that in case of having a single phase or one three-phase system total section will be calculated by dividing by 1,8 the previous section. This number has been set taking into account that enough space is left for maintenance works.

To come with a cost calculation model, cost is only estimated for the tube civil works. The method used expresses the cost per longitudinal meter of the tunnel, in reference to the variables RMR index and the excavation section (S) [27]. The RMR is an index that gives a classification of the hardness of the rock being excavated.

Total cost of tunnelling is calculated[27]:

$$C_{tunnelling} = (83.93 * S - 148{,}189 * RMR + 9578.3) * l \qquad (23)$$

where;

$C_{tunnelling}$: cost of tunnelling [€/m]

S: section [m^2];

RMR: index;

l: length [m].

3.4.3.3 Multipurpose tunnels

An appropriate way for cost reduction when tunnel laying is necessary, it is to share the structure with other users. Two different principles of multipurpose tunnels can be seen. Firstly Round Tunnels, made by a boring machine which gives a round section to the tunnel. Usually, as the floor is needed to be flat, the space between the road and the concrete panels can be used to fix the GIL pipes. This type of tunnels are shown Figure 21.

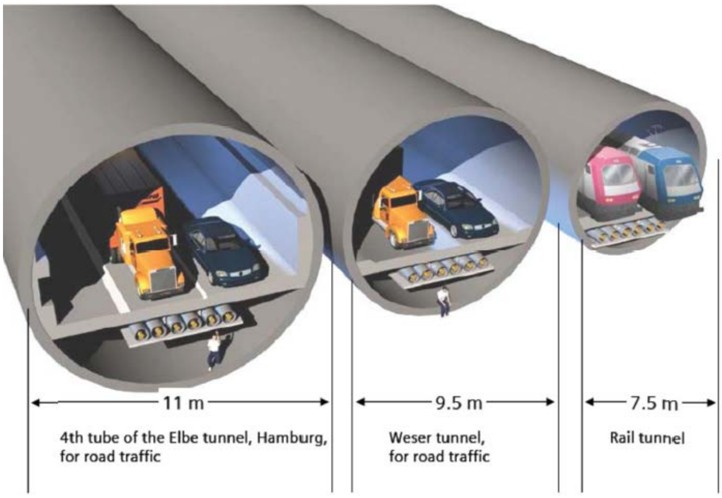

Figure 21 Multipurpose tunnels. Round Tunnels (Data source: [22])

Secondly, those tunnels which have been constructed in the traditional building process known as 'Drill and blast'. There is the possibility to fix the GIL pipes on the roof. This type of tunnels are shown in Figure 22.

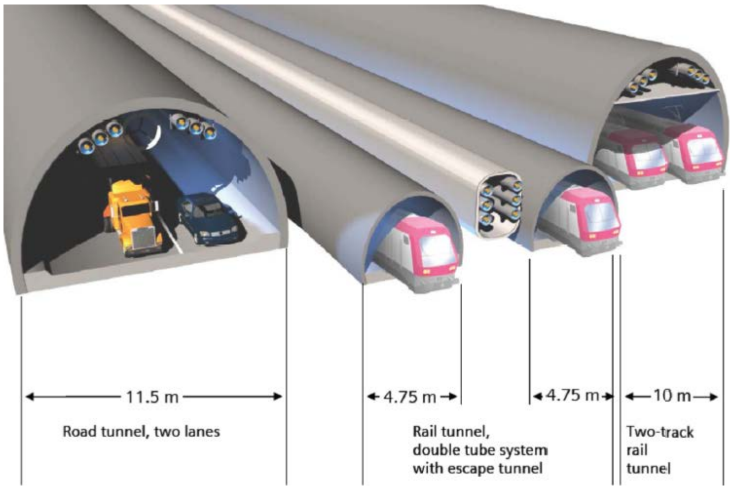

Figure 22. Multipurpose tunnels. Drill and blast (Data source: [22])

To come up with the price of this laying method we will consider the cost calculation method for above-ground installations (see chapter 3.4.4).

3.4.4 Above ground installations

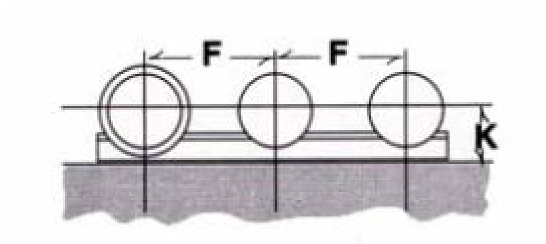

Figure 23. Above ground installation. (Data source: [16])

The above ground installation system is the one with the cheapest civil works cost. It is because of the simplicity and the low use of materials when installing it. Normally above ground installations are the choice for rural places where there are no environmental restrictions.

In this case the cost of the steel fixing structures is dismissed as it has been done in other laying methods; in this case as well as in the others, the steel structures are situated at 100-120 m [22]. Regarding the land clearing costs they can be approximated to 1,03 €/m^2 . Also the foundations cost has to be calculated. Price per foundation is 194 €/m^3 [24].

Approximately the cost of each foundation is around 100-150 € and is situated at 100-120 m. As the price of the pipes is around 40.000- 80.000 € per 100-120 m the cost of foundations and land clearing is also dismissed. Therefore, this the total cost of above ground laying will be considered as nil.

3.5 Cost dependency on Gas quantity

3.5.1 SF_6 + N_2

The development of GIL second generation was aimed to reduce the amount of SF_6 used, because of its high cost which did condition GIL implementation. As a consequence, another gas mixture was introduced, being much cheaper and with a lower impact on the environment ($N_2 + SF_6$). However with the second GIL generation gas still represents a problem for this technology as it is still highly pollutant and also expensive.

The gas mixture composition nowadays mostly used is 80% N_2 and 20% SF_6 in volume. This gas mixture has to provide similar rates of electrical insulation as first generation GIL with 100% SF_6 does. In order to accomplish it, it can be done by modifying the gas pressure. This increase on the gas pressure has an effect on the conductor diameter and the outer enclosure wall thickness dimensions.

In order to give a relationship between gas quantity and voltage, values from GIL projects are provided in [19], where quantity of gas is expressed in kg of SF_6 per phase meter. This values are shown in Table 14.

Table 14. Mass of SF6

Voltage(kV)	160	242	300	362	480	800	1200
Mass (kg)	1,13	2,13	3,02	3,3	5,72	8,77	13,21

In Figure 24 is shown the statistical regression between mass of SF_6 and rated voltage.

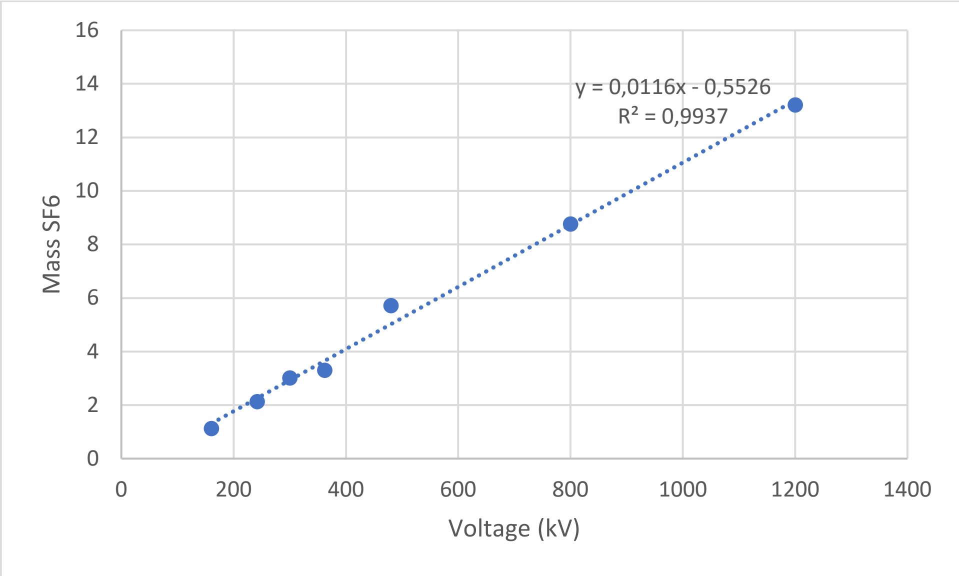

Figure 24. Mass of SF_6.

The equation that approximates the mass of SF_6 per phase and meter:

m = 0,0116V - 0,5526 (24) R^2 = 0,9937

where;

m: mass [kg];

V: voltage phase-phase [kV].

In order to calculate the amount of mass of N_2 per phase and meter it is considered that the gas is working under ideal conditions. The equation of the ideal gases is used to get to know the necessary mass of N_2.

$$PV = nRT \quad (29) \qquad n = \frac{m}{M} \quad (25)$$

As it is known, the volume occupied by N_2 is 80% and using both equations (29), (30), the mass of N_2 is calculated as:

$$m_{N2} = \frac{0,8}{0,2} * \frac{m_{SF6} * M_{N2}}{M_{SF6}} \quad (26)$$

And volume:

$$V_{N2} = \frac{\frac{m}{M} RT}{P} \quad (27)$$

where;

m: mass [kg];

M: molecular mass [kg/mol] $M_{N2} = 0{,}028\ \mathrm{kg/mol}$

$M_{SF6} = 0{,}146\ \mathrm{kg/mol}$;

P: pressure (0,082) $[\frac{\mathrm{atm\ L}}{\mathrm{mol\ K}}]$;

n: number of mols;

T: temperature [K].

As a result the total cost for gas in a single-phase GIL is calculated as:

$$C_g = C_{N2} + C_{SF6} = d * (m_{N2} * p_{N2} + m_{SF6} * p_{SF6}) = d * (\frac{0{,}8}{0{,}2} * \frac{m_{SF6} * M_{N2}}{M_{SF6}} * p_{N2} + m_{SF6} * p_{SF6}) \qquad (28)$$

Whereas in a three-phase GIL system is:

$$C_g = C_{N2} + C_{SF6} = 3 * d * (m_{N2} * p_{N2} + m_{SF6} * p_{SF6}) = 3 * d * (\frac{0{,}8}{0{,}2} * \frac{m_{SF6} * M_{N2}}{M_{SF6}} * p_{N2} + m_{SF6} * p_{SF6}) \qquad (29)$$

where;

m: mass [kg per phase and m];

p: price [€/kg] (the price for 5kg of SF_6 is 351,8 € with the exchange rate $ to €: 1,1 $ is 1€).

d: distance [m].

3.5.2 CF_3I

As the gas mixture mainly used is a highly pollutant gas. In the future the N_2 and SF_6 gas mixture is going to be replaced by an alternative gas with lower greenhouse effect, for example trifluoroiodomethane (CF_3I). CF_3I is an alternative for being a more environmental friendly gas; the weak chemical bond C-I in CF_3I means that it can be decomposed quickly in the atmosphere and the global warming potential and the ozone depletion consequences are extremely low.[12]

In reference to [28], pure CF_3I has a dielectric strength 1,2 times higher than pure SF_6. However, CF_3I cannot be used alone as it has a high boiling point at working conditions (0,7 MPa), around 26ºC. Notice that the boiling point for SF_6 is -64ºC [29]. A solution to avoid having the gas liquefied at such low temperature is to mix the gas with other gases such as N_2, air or CO_2. Further research on this gas and other alternatives is necessary to be done in order to find a proper alternative for SF6.

3.6 Assembly, testing and transport cost

The principles used for the assembly and transport works are the same as the ones used for pipelines that is pipe segments are transported and welded on site. The cost approximation is complex as it depends on parameters as transport lengths, site conditions and accessibility.

The maximum transport length is defined by restrictions given by the transport regulation. This restrictions may modify the number of welded joints needed, including their respective quality testing. One joint takes 4 hours for three workers. This shows how the maximum transport length has an impact on the project cost. [4]

To assemble the GIL, the installation site needs to be accessible by truck to be able to deliver the enclosure and conductor pipe. Although not being heavy, pipes do need much space; furthermore the simultaneous work may need some space to store pipes and other materials. Finally the installation process is done. It consists of a welding process, normally done close to site, where all the segments of pipes are jointed with a spiral welding machine.

The procedure of testing is related to those activities to ensure that the installation complies the law standards. A quality insurance plan is followed during and after the assembling, to ensure the quality of the joints. Also there is a high voltage power frequency electrical test, which ensures the electric safety of the line.

As far as the cost of assembly and transport is concerned, which refers to on-site pre-assembly , on-site transportation , laying in the trench or pulling into a tunnel, welding the joints , fixing on steel structures, on-site testing and commissioning. The total cost of all this components is in reference to [11] equal to the cost of all materials used in the installation.

$$C_{tit} = C_g + C_{angle\ units} + C_{disconnecting\ units} + C_{Conductor} + C_{Outer\ enclosure} \quad (30)$$

where;

C_{tit}: Cost of transport, installation and testing [€].

3.7 Life-long costs

3.7.1 Power losses and power transmission capacity reduction due to reactive power cost calculation

The cost of lost energy represents the major component of the lifetime operational costs [13]. On the one hand, the power losses in GIL are caused by the intensity flowing through the conductor and the conductor's resistivity. Generally, due to the large conductor section, GIL has got lower power losses than OHL [4]. It is a significant point that encourages the use or at least the study of this transmission methodology.

On the other hand, the reactance component of the transmission lines causes a reactive power consumption or generation that limits the total active power transfer; that is, a change in the phase relation between voltage and current is produced. Part of the energy transported is converted into another form of energy; this new energy form if not compensated is not more useful. Normally GIL has lower reactive impedance than overhead or underground lines [4].
In this thesis, a transmission line operating for a given number of working hours at nominal rates is supposed for cost calculation purposes. This line could represent the connection between a generation and a load point.

In order to do the economic study of this cost component, the equivalent pi circuit of an electric line used to study power losses costs and power transmission capacity reduction due to reactive power reactive cost. This pi circuit is shown in Figure 25.

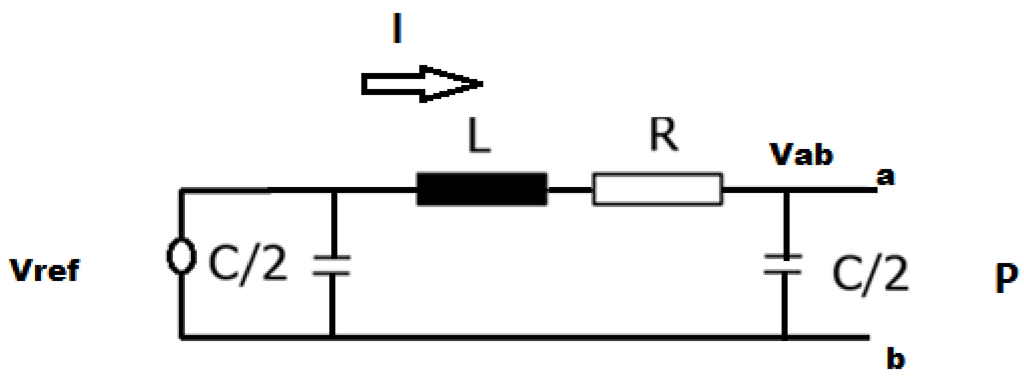

Figure 25. Equivalent PI circuit of an electric line.

where;

V_{ref}: is the voltage the beginning of the interconnection;

C: equivalent capacity;

L: equivalent inductance;

R: equivalent resistance;

I: intensity;

V_{ab}: voltage in the load (phase-neutral);

P: active power consumed by the load.

In order to calculate power losses and reactive power consumption or generation, the following assumptions have been done:

- V_{ref} phase is 0º.
- The apparent power at the load side is assumed as full active power (cos ϕ =1).

To come up with power losses and the reactive power in the line, intensity flowing by the inductance, capacitor and resistance must be calculated. In Figure 26 the equivalent of Thevenin is shown as it is used to calculate voltage in the load V_{ab} (phase-neutral). Knowing V_{ref} and V_{ab} we are able with this valuess to calculate the intensity I flowing through the equivalent resistance and inductance in the pi circuit (see Figure 25).

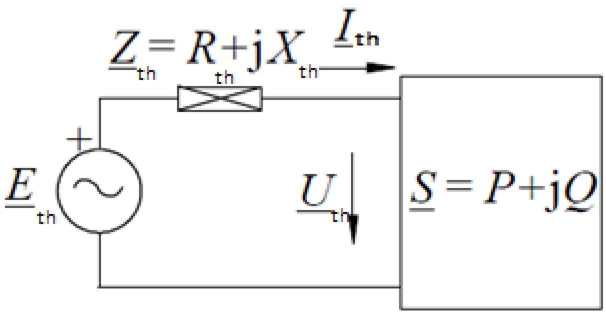

Figure 26. Thevenin equivalent circuit. (Data source: EE ETSEIB)

All parameters indicated in Figure 26 are associated to the Thevenin's theorem.

The parameters of the Thevenin theorem Eth and Zth are calculated to provide Uth=Vab which refers to the voltage in the load:

1. Eth = Vab when no load is connected to the transmission circuit.

$$\underline{V}_{AB} = \frac{-2jX_c}{-2jX_c + jX_L + R}\underline{V}_{ref} \tag{31}$$

2. $\underline{Z}$th which refers to the equivalent impedance of Thevenin when the voltage sources are short-circuited and the intensity sources are opened.

$$\underline{Z}\text{th} = \frac{-2jX_C\,(-2jX_C+jX_L+R)}{-4jX_c+jX_L+R} \tag{32}$$

where;

$\underline{Z}$th: Thevenin's impedance [Ω];

R: Resistive impedance [Ω] (referred to Figure 25);

X_C: Capacitive impedance [Ω] (referred to Figure 25);

X_L: Inductive impedance [Ω] (referred to Figure 25).

Finally the following equation is solved in order to get V_2= Uth = Vab. Values associated to this Thevenin equation are related to values shown in Figure 26.

$$V_2^4 + V_2^2\left(2R_{th}P + 2X_{th}Q - {E_{th}}^2\right) + \left({R_{th}}^2 + {X_{th}}^2\right)(P^2 + Q^2) = 0 \tag{33}$$

where;

R_{th}: Equivalent Thevenin's resistance [Ω] (referred to Figure 25);

X_{th}: Equivalent Thevenin's reactive impedance [Ω] (referred to Figure 25);

P: Power consumed in the load (referred to Figure 25);

Q: Reactive power consumed or generated in the load (referred to Figure 25).

In this case all the variables are associated to Figure 26. In order to calculate voltage in the load (V_2= Vab), it is calculated with the following equation:

$$\underline{V}_2 = \underline{Z}_{PQ}\underline{I}_{th} \tag{34}$$

We have to know values of Z_{PQ} which refers to the impedance of the load and I_{th} which refers to the Thevenin's intensity. Following equations are used to come up with the V_2 value.

$$\underline{Z}_{PQ} = \frac{U_{th}^2}{\underline{S}^*}$$

$$\underline{I}_{th} = \frac{\underline{E}}{\underline{Z}+\underline{Z}_{PQ}} \tag{35}$$

Finally, once that we know V_2 (phase to neutral voltage), it can be calculated the intensity through the resistance and inductance in the PI circuit (Figure 25). Intensity is used to calculate the power losses in the resistance due to Joule's effect, and to calculate the reactive power consumed in the inductance. On the other hand, V_2 is used as well as V_1=V_{ref} to calculate the capacitive power generated in the condensator.

$$\underline{I} = \frac{\underline{V_1} - \underline{V_2}}{R + jX_l} \qquad (36)$$

All this calculus are referred to single phase systems. In case of three phase systems it has been used the single phase equivalent by using Vref as voltage between phase and neutral. Then to calculate energy losses and reactive power, the results should be multiplied by 3.

3.7.1.1 Power losses

In order to come up with power losses values it is necessary to know the resistance parameter. The line resistance depends on the outer enclosure diameter and the wall thickness of the outer enclosure and conductor pipe[11], turn, they depend on the voltage rating. Active power transmission losses are related to the square of the transmitted current as:

$$P_l = R * I^2 \qquad (37)$$

This values shown in the previous equation are referred to Figure 25.

To create the cost calculation tool, it has been necessary to approximate resistance per phase and m for each voltage rate. Data from two different bibliographic sources Table 15 from [19] and Table 16 from [16] have been collected:

Table 15. Resistance. (Data source: [19])

Voltage (kV)	138	230	345	500
μΩ/m	26,017	17,257	12,598	9,186

Table 16. Resistance (Data source: [16])

Voltage (kV)	145 / 170	245 / 300	362	420 / 550	800	1200
μΩ/m	18	16	13	11	10	8

In Figure 27 is shown the statistic regression between resistance (μΩ/m) and rated voltage kV.

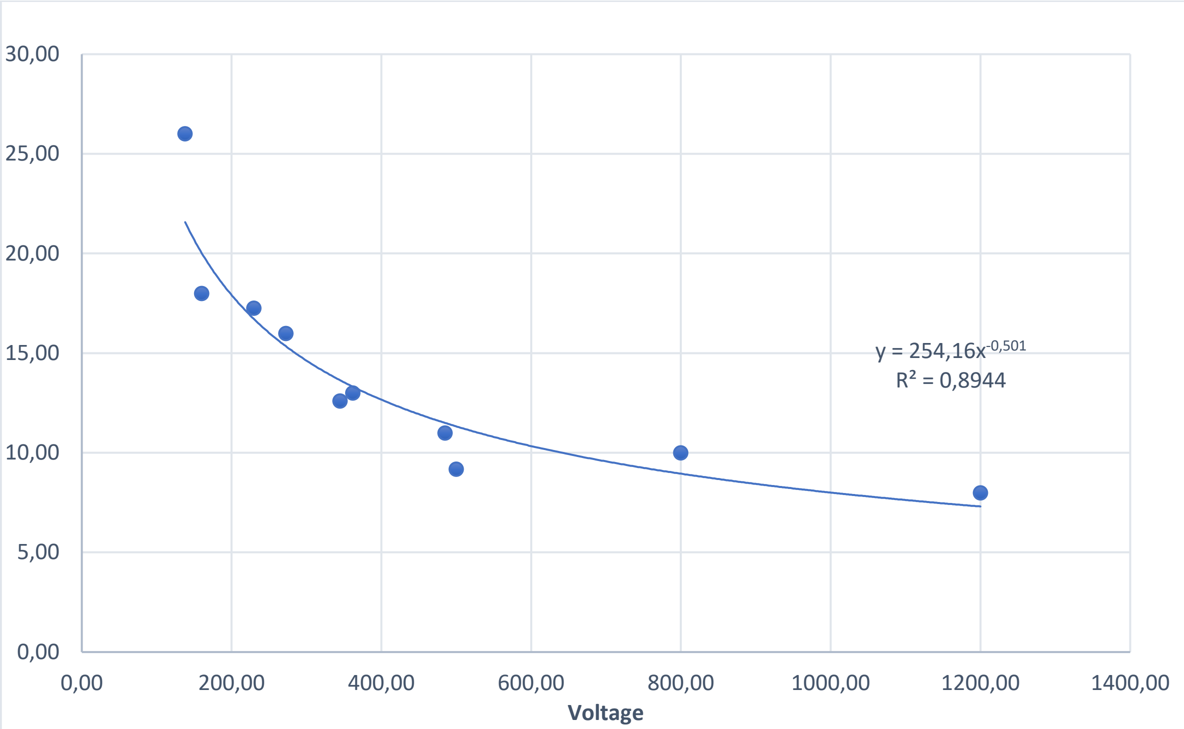

Figure 27. Resistance per m.

$r = 254{,}16V^{-0{,}501}$ (38) $R^2 = 0{,}8944$

where;

r: resistance [μΩ/m];

V: voltage [kV].

The power losses cost is calculated as the cost of the energy not sold during the working hours of the life-time period of the GIL infrastructure. The quantity of working hours per year considered are 8760 h. The energy selling prices have been taken by default as 50 €/MWh [30].

Depending on the type of transmission system (single-phase and three-phase), yearly cost of losses are expressed as:

- Single-phase:

$$\mathrm{Pl} = 10^{-6} * \mathrm{r} * \mathrm{I}^2 \quad (39a)$$

$$\mathrm{Cost}_{\mathrm{APL}} = 10^{-12} * \mathrm{r} * \mathrm{I}^2 * \mathrm{nH} * \mathrm{C_e} * \mathrm{d} \quad (40a)$$

- Three phase:

$$\mathrm{Pl} = 3 * 10^{-6} * \mathrm{r} * \mathrm{I}^2 \quad (39b)$$

$$\mathrm{Cost}_{\mathrm{APL}} = 10^{-12} * 3 * \mathrm{r} * \mathrm{I}^2 * \mathrm{nH} * \mathrm{C_e} * \mathrm{d} \quad (40b)$$

where;

$\mathrm{Cost}_{\mathrm{APL}}$: cost € power losses in a year of working GIL system [€];

nH: number of working hours per year: 8760 h [13];

$\mathbf{C_e}$: cost of energy [€/MWh];

r: resistance per meter [µΩ/m];

d:distance of the line [m];

I: intensity [A] see Figure 25.

In order to present the value of the sum of the annual total costs of the power losses over the n years of the project lifetime, $\mathrm{E_A}$, can be obtained[13]:

$$\mathrm{E_A} = \frac{(1+\mathrm{i})^{\mathrm{n}}-1}{\mathrm{i}(1+\mathrm{i})^{\mathrm{n}}} * \mathrm{Cost}_{\mathrm{APL}} \qquad (41)$$

where;

n: installation's number of years of life;

i: discount rate (per unit).

3.7.1.2 *Power transmission* capacity reduction due to reactive power

Reactive power are a consequence of the inductance and capacitance of the transmission line. Reactive power generated or consumed in a transmission line reduces the total capacity of active power transmission for a line. Until now, only AC GIL systems have been developed as a consequence of problems in the development of DC GIL systems [11].

In GIL installations, over long distances of 60-80 km, no reactive power compensation is required [11]. In this thesis the utilization of compensator units is considered; when the ratio Q/P>0,2 [13], which P and Q refer to:

- P: power consumed by the load (see Figure 25).
- Q: reactive power at the beginning of the GIL infrastructure, referring to the reactive power that is consumed or generated by the GIL installation, so that the assumption done that in the load the power is fully active is accomplished. (See Figure 25)

Nevertheless in case the ratio Q/P is lower than 0,2 (no compensator unit is used) all the reactive power consumed or generated in the line is considered in the cost calculation, as a reduction of the capacity of active power transmission.

Firstly, to calculate the value of capacitive power, data of capacitance of different GIL projects have been obtained to give a relationship between capacitance and voltage rates. Capacitance is expressed in picoF/m and is referred to a single phase. Values are shown in Table 17 and Table 18.

Table 17. Capacitance. (Data source: [16])

Voltage (kV)	145	242	362	550	800	1200
pF/m	59,5	52,6	53,1	54,2	45,1	42,7

Table 18. Capacitance. (Data source: [19])

Voltage (kV)	138 kV	230 kV	345 kV	500 kV	750 kV
pF/m	56,743	46,364	44,500	46,364	42,138

In Figure 28 is shown the statistic regression for the capacitance value (picoF/m) for each rated voltage (kV).

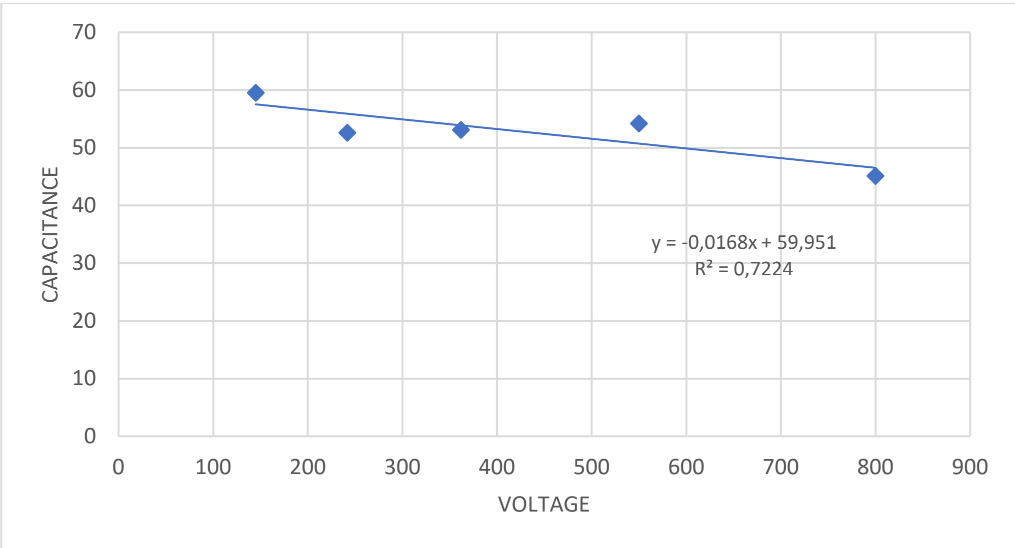

Figure 28. Capacitance.

$C = -0{,}0168V + 59{,}951$ (42) $R^2 = 0{,}7224$

where;

C: capacitance per phase and meter [pF/m]

V: voltage [kV]

To calculate total capacitance reactive power:

- Single phase:

$$Q_c = \frac{|V|^2}{Z^*} = -\frac{4\pi * freq * c}{10^{12}} * (|V_1 * 10^3|^2 + |V_2 * 10^3|^2) * d \qquad (43a)$$

- Three phase:

$$Q_c = j\,3 * \frac{4\pi * freq * c}{10^{12}} * (|V_1 * 10^3|^2 + |V_2 * 10^3|^2) * d \qquad (43b)$$

where;

Q_c: capacitive power [VAr];

C: capacitance per phase and meter [pF/m];

freq: frequency [Hz] (in the tool used the European frequency 50Hz);

V: voltage (kV) (see Figure 25);

d: distance [m].

Secondly to calculate the inductive power of the conductor, data of inductance from different GIL projects are collected to come up with a relationship between inductance and voltage. Inductance is expressed in μH/m and referred to a single phase. Values are shown in Table 19 and Table 20.

Table 19. Inductance

Voltage (kV)	138	230	345	500
μH/m	0,196	0,211	0,209	0,209

Table 20. Inductance

Voltage (kV)	145	242	362	550	800
μH/m	0,187	0,211	0,210	0,205	0,247

In Figure 29 is shown the statistic regression of the inductance parameter (µH/m) related to each rated voltage.

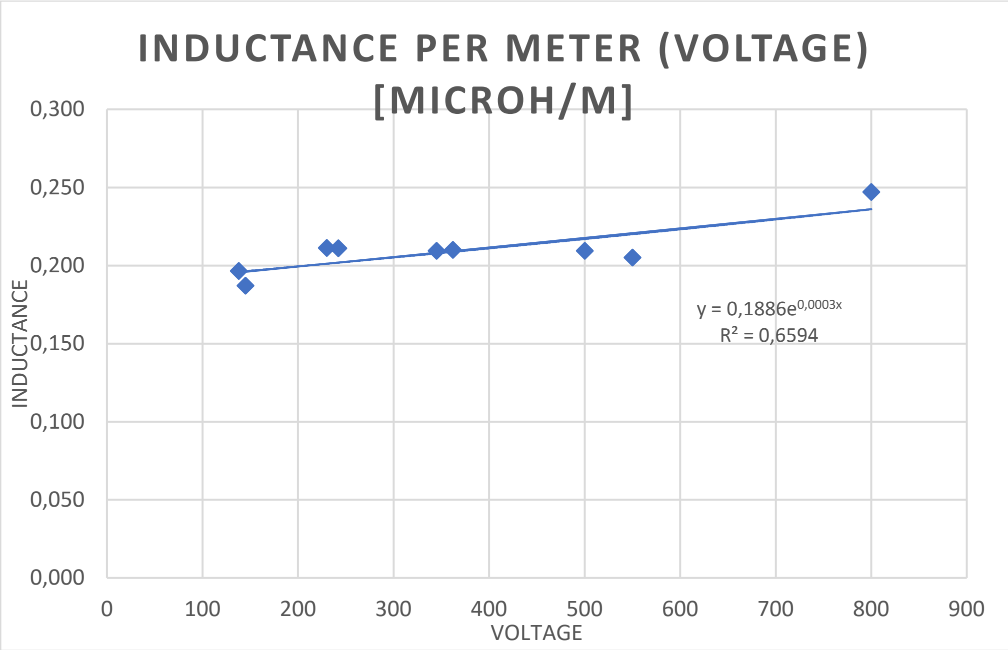

Figure 29.Inductance.

$L = 0{,}1886e^{0{,}0003V}$ (45) $R^2 = 0{,}6594$

where;

L: inductance per meter [µH/m]

V: voltage [kV]

To calculate inductance reactive power per year:

- Single phase:

$$Q_I = 10^{-6} * (2 * \pi * freq * L * I^2 * d) \quad (46a)$$

- Three phase:

$$Q_I = 3 * 10^{-6} * (2 * \pi * freq * L * I^2 * d) \quad (46b)$$

where;

Q_I: inductive power [VAr];

I: current flowing in the PI circuit (see Figure 25) [A].

The cost related to the reduction of power transfer due to reactive power is calculated in a similar way to the power losses. This cost is associated to the reduction of the transmission capacity, that means energy that cannot be transmitted. The cost associated to the reactive power in the GIL system $(Q_I - Q_C)$, is approximated by calculating the subtraction between total cost of energy at the beginning of GIL and power consumed in the load and in the circuit due to losses $(S_{generator} - P - P_l)$.

The power at the beginning of GIL is calculated with the following equation:

$$S_{generator} = \sqrt{(P + P_l)^2 + (Q_I - Q_C)^2} \qquad (47)$$

Referring to cost of reduction of transmission capacity due to the reactive power per year:

$$Cost_{RP} = \left(S_{generator} - P - P_l\right) * nH * C_e \qquad (48)$$

where;

P: total power consumed in the load [kW];

P_l: total power losses in the GIL infrastructure [kW]

$Cost_{RP}$: cost of reactive power [€/year];

nH: number of working hours per year [h];

$\mathbf{C_e}$: cost of energy [€/kWh];

In order to present the value of the sum of the annual total costs over the n years of the circuit lifetime, E_R is obtained[13]:

$$E_R = \frac{(1+i)^n - 1}{i(1+i)^n} * \ Cost_{RP} \qquad (49)$$

where;

i: discount rate.

n: installation's number of years of life.

Finally, total cost of power losses and the cost related to reduction of power transfer due to reactive power is calculated as:

$$E_T = E_A + E_R \qquad (50)$$

3.7.1.3 Transmission length and phase compensation

The limiting length without the use of phase compensation is of high importance in order to calculate total cost of the transmission line. The criteria used to determine the use of compensators is the ratio Q/P=0,2 (cosφ=0,98), where P refers to active power consumed by the load.[26]

In case GIL does not need reactive power compensation (Q/P < 0,2), this reactive power can be quantified in costs as the extra fuel needed to be consumed to produce the power that finally is converted into reactive power; note that all this reactive energy transmitted that cannot be used, causes an increase on the price of the installation. That means a power infrastructure is designed by rates of voltage and apparent power. In this first case as reactive power is not compensated the infrastructure must be over dimensioned.

In case the ratio Q/P is greater than 0,2 reactive compensation devices are used. There are two main options, fixed-value compensators, and variable compensators. On the one hand, fixed value compensators, such as shunt reactors are cheaper and occupy less space, but the compensation rates are fixed. On the other hand, variable compensators such as STATCOMs (Static Synchronous Compensator) are more expensive, but they can compensate exactly each value desired in each moment.

If it is the case of constant working parameters, the variation of the reactive power is low. In this case, the compensation method used is a mixture of a base constant compensation (shunt reactor) and an additional compensation capacity given by the variable compensation done by STATCOM.

From [30] is obtained the cost of a shunt reactor and a STATCOM compensator.

- STATCOM:

The approximate cost is 0,086 M€/MVAr.

- Shunt reactors

The cost of reactors is set at 0,01 M€/MVAr.

In order to calculate the cost of compensation a ratio that accounts the variation of reactive power is introduced to calculate the cost of the STATCOM compensator.

$$\mathrm{C_{compensation}} = 0{,}01 * |\mathrm{q_{tot}}| + 0{,}086 * \mathrm{R} * |\mathrm{q_{tot}}| \quad (51)$$

where;

$\mathrm{C_{compensation}}$: cost of the compensators [M€];

q_{tot} : total reactive power generated by cables [MVAr];

R: ratio of variability of reactive power.

Compensator systems also have their own power losses. Losses of a shunt compensator are similar to the transformer losses as both are built similarly. They are reported as 0,2% of the transmitted power. In this case, as STATCOM working states are variable, their losses are not accounted.

$$P_{losses\ reactor} = 0{,}002 * |S_{load}| \qquad (52)$$

$$Cost_{LR} = P_{losses\ reactor} * nH * C_e \qquad (53)$$

where;

$P_{losses\ reactor}$: power losses in the reactor [MW];

nH: number of working hours per year [h] (8760 h) [13];

$\mathbf{C_e}$: cost of energy [€/MWh]

Total cost of lost power during the life long cycle of the GIL infrastructure:

$$E_A = \frac{(1+i)^n - 1}{i(1+i)^n} * Cost_{LR} \qquad (54)$$

3.7.2 Operation and maintenance cost

Maintenance costs for GIL are estimated as a percentage of the total initial investment cost. Maintenance is performed at regular intervals for preventive purposes, and consists of inspections, monitoring and periodically maintenance activities.

The costs for the routinely maintenance activities for GIL for a year, being referred to the original investment [13], are calculated with values shown in Table 21.

Table 21. Operation and Maintenance costs

Annual cost	Percentage of total initial cost
Operation	0,1-0,3%
Maintenance	0,1%
Sum	0,2-0,4%

The cost value for the life-long operation of a GIL system ($C_{O\&M}$) is calculated as:

$$C_{O\&M} = \frac{(1+i)^n - 1}{i(1+i)^n} x \ OM \qquad (55)$$

where;

$C_{O\&M}$: cost life-long for operation and maintenance [€];

n: is the lifetime in years;

OM: is the cost of maintenance and operation per year [€].

3.8 Distance non-dependent costs.

These costs refer to GIL testing, terminations and transformers. Whilst there is some variation due to length in the cost of testing this value is included in the end cost as fixed cost for each length[26].

3.8.1 GIS (GIL terminations)

The technology normally used is gas insulated switchgear (GIS). It is more used than air insulated switchgear, because of its operation reliability and its lower need of maintenance [31]. In a GIS substation the equipment accounted as costs is the GIL-GIS interface module; additional angular tubes installed, and the steel structures required to support.

From [5] [30] we obtain data to get the equation for the cost estimation of a UHV GIS; the price has been obtained in million **€**. The exchange rate £ to € is 1 £ is 1,06 €. Information about the price in relationship with voltage is shown in *Table 22*

Table 22. Price of GIS.

Voltage (kV)	33 kV	150 kV	220 kV	275 kV	400 kV
M€	0,424	1,166	2,385	2,862	3,763

$C_{GIS} = n\ (0{,}0096\ U + 0{,}0543)$ (56) $R^2 = 0,\ 9713$

where;

C_{GIS}: cost of GIS [€];

n: number of GIS;

U: phase to phase voltage [kV].

3.9 Project launch and build contingency

Project launch and management costs are those costs related to the engineering projection of the infrastructure. They are an approach of those activities that are required to design and to prove the feasibility. This costs are around 20% of the total construction cost including build contingency [26]. The construction cost is referred to the cost of pipe production, installation, testing, and the gas synthetization.

$$C_{PL} = 0{,}2 * C_b \qquad (57)$$

where;

C_{PL}: cost of project launch and management [€];

C_b: sum of the construction cost [€].

As far as the contingency cost is concerned, this is a provision for items that have been omitted, neglected and for those elements that would require an unnecessary level of detail for this report.

This contingency cost is approximated to 15% of the sum of the costs of the fixed materials that are not related to length and those which do depend on infrastructure length. It takes into account their installation and testing and it accounts the cost of the termination compounds and the reactors. It is remarkable that the contingency cost does not include the lifelong costs related to energy losses and the reactive power or even maintenance and reparation, also it does not include the project launch and management. [26]

$$C_{contigency} = 0{,}15 * C_t \qquad (58)$$

where;

$C_{contingency}$: cost contingency [€];

C_t: sum of costs mentioned [€].

4 Case study

The studied case corresponds to a new AC electric line in Spain. It consists of a reinforcement of the transmission grid between Valencian Community and Castilla – La Mancha. In this case, it will be studied specifically a transmission line of 400 kV Pinilla-Ayora-Cofrentes. This new line will provide an increase in the security of supply and quality of electricity, especially for the Valencian province.

In this new line it is of interest the study of different approaches as solution because it goes through different natural protected areas and close to inhabited places. In Figure 30 is shown the route (inside a circle) where the new transmission line is going to be constructed.

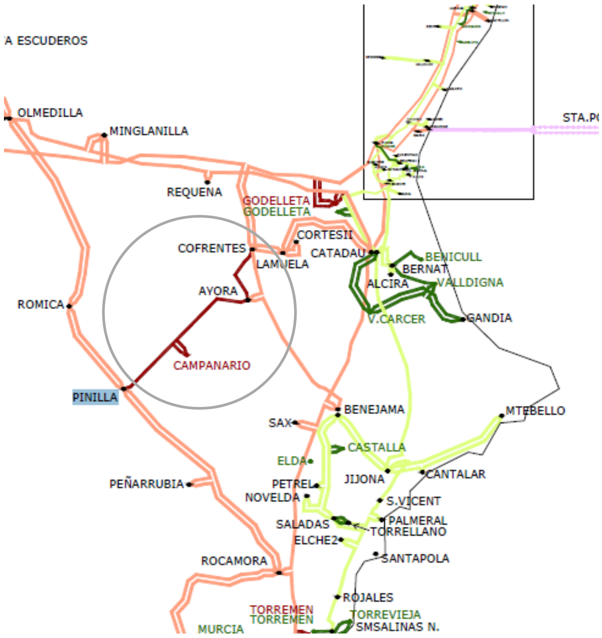

Figure 30. New electric transmission line. (Data source: [31])

The nominal values for the new infrastructure defined by the company Red Eléctrica de España are shown in Table 23.

Table 23. Nominal values for the infrastructure. (Data source: [31])

Nominal power	2441 MVa
Nominal voltage	400kV
Maximum voltage	420kV
System length	95 km
Frequency	50Hz
Initial point	Pinilla (Albacete)
Final point	Cofrentes (Valencia)

In this study it is compared the use of overhead and underground lines with GIL. For every transmission system it has been considered the use of the additional data shown in Table 24.

Table 24. Important data.

Usage power factor (%)	100%
Lifelong (years)	40
Discount Rate (per unit)	0,05
Working hours per year	8760
Cost of energy (€/MWh)	50
Number of phases	3
Number of parallel units	1
Number of transformers	0
Number of GIS units	2

Note that two GIS units are used, one at the beginning and another at the end of GIL. This two units ensure the protection of the system isolating the GIL from the rest of the transmission grid.

Remember that in case a system has a greater ratio Q/P>0,2 then compensation units are used and the cost for its losses is accounted. If this ratio is lower than 0,2 no compensation is done.

4.1 GIL cost study and sensitivity

It is interesting to do a cost study of the GIL infrastructure in this new line because this project goes through important green habitats known as the Valle de Ayora and Sierra del Boquerón in Valencia and Albacete respectively; another point is that the new line is located close to the town of Teresa de Cofrentes, potentially causing a negative impact on its population [32]. The advantages of GIL mentioned in Chapter 2 make GIL an interesting technologic solution.

The factors that make GIL a feasible option is that this system has high safety rates against fire. Also the electromagnetic fields outside the outer enclosure are low, what can determine the use of one or other type of installation.

Some important data to come with the cost estimation of the GIL infrastructure is shown in Table 25:

Table 25. Material prices

Price Al outer enclosure	4,2€/kg [33]
Price Al conductor	5,2 €/kg [34]
Price SF_6	70,5 €/kg [35]
Price N_2	7,1 €/kg [36]

In the cost study estimation it has been considered that the laying system is directly buried in its whole length to avoid problems that would cause an OHL infrastructure. This laying method has been decided in reference to the environmental impact study presented in [32] where it can be inferred that it is important to reduce as much as possible the visual impact and effect on the natural places.

It is observed that a total number of three angle units are needed according to the route of the new line. All of them situated near the town Ayora. This is caused by the existence of a mountain range. In Figure 31 it is shown the route of the new line.

Figure 31. Route. (Data source: Google Maps)

4.1.1 Cost study of GIL

In the cost study, the cost has been divided in two different components, initial investment (shown in *Table 26*) and life-long costs.

1. Initial investment

Table 26. Initial investment

	Million €	€/m	€/MVA
Pipe + Conductor	54,7	576,1	22.421,3
Civil works	5,6	59,0	2.296,2
Gas (N_2+ SF_6)	88,5	931,6	36.258,1
Routing (angle + disconnecting units)	0,3	3,0	117,7
Transport, installation testing	143,5	1.510,8	58.797,1
GIS + Compensator	9,5	99,6	3.876,4
Project contingency	45,3	477,0	18.565,0
Project management and launch	40,8	429,3	16.706,9
Total fixed costs	**388,2**	**4.086,5**	**159.038,6**

It is noted the importance of the aluminium pipes, gas and transport, installation and testing on total cost. That confirms what is stated in [11] that a normal distribution of the initial cost of investment is 40 % for materials (gas, pipes, angle units, and disconnecting units), 40% for installation, transport and testing and finally 20% is for project launch, management and engineering. In Figure *32* is shown the initial investment distribution.

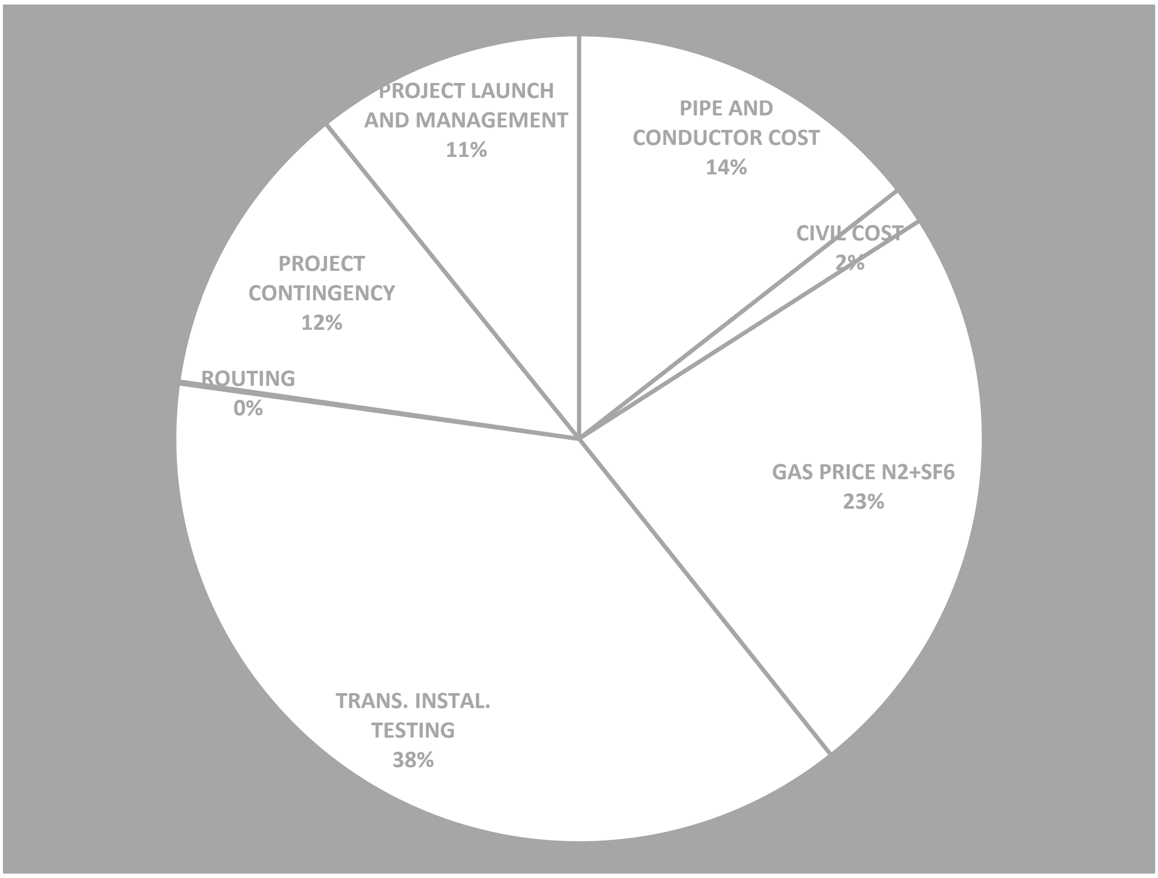

Figure 32. Initial investment.

Remark that the component routing refers to those components of the pipes that are angle units, disconnecting units, male and female sliding contact, and compensators.

2. Life-long costs

Note that this costs have been calculated for the whole project lifetime of the line which is considered 40 years. The discount rate index is assumed as 0,05. Furthermore, as the ratio Q/P<0,2 (see chapter 3.7.1.2) there are no compensation units and reactive power reduces the maximum capacity of the line. In Figure 33 is shown the cost distribution of the variable costs, and in Table 28 are shown all the variable costs.

The values of resistance, capacitance and inductance calculated by the tool are shown in Table 27.

Table 27. RLC values

Line Data	R [Ω/km]	L [mH/km]	C [µF/km]
	0,0126	0,21	0,053

Table 28. Variable costs.

	Million €	€/km	€/MVA	€/year
Power losses	85,8	902,7	35.130,0	2.143.805,9
Cost reduc.Transm. Capac	5,6	58,7	2.285,0	139.444,4
Power losses in the compensation unit	0,0	0,0	0,0	0,0
Operation and maintenance	29,4	310,0	12.063,2	736.158,8
Total variable costs	**120,8**	**1.271,3**	**49.478,2**	**3.019.409,0**

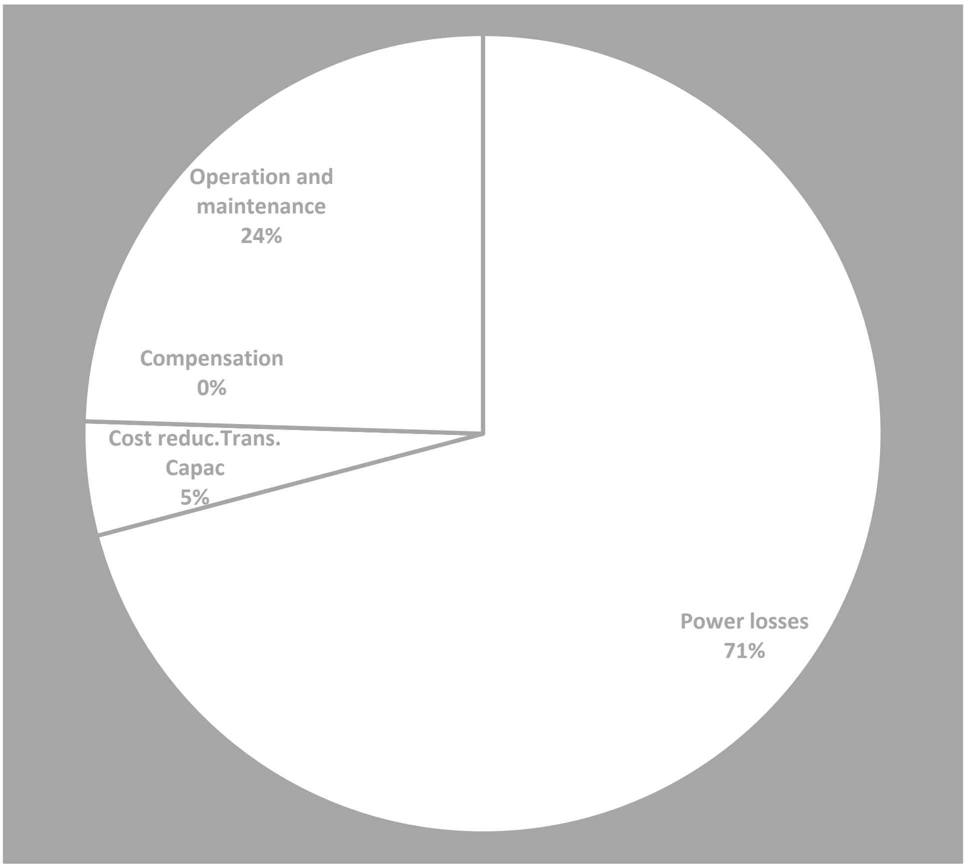

Figure 33. Life long cost distribution.

In this distribution it can be confirmed that transmission what is reported in [11] that power losses are the major factor of the operation cost. They represent the 80% of the total variable costs.

3. Total cost

In Table 29 are shown total cost values, and in Figure 34 is shown the cost distribution.

Table 29. Total cost

	Million €	€/km	€/MVA	€/year
TOTAL COST	509,0	5.357,8	208.516,8	3.019.409,0

In Figure 34 is shown the total cost distribution.

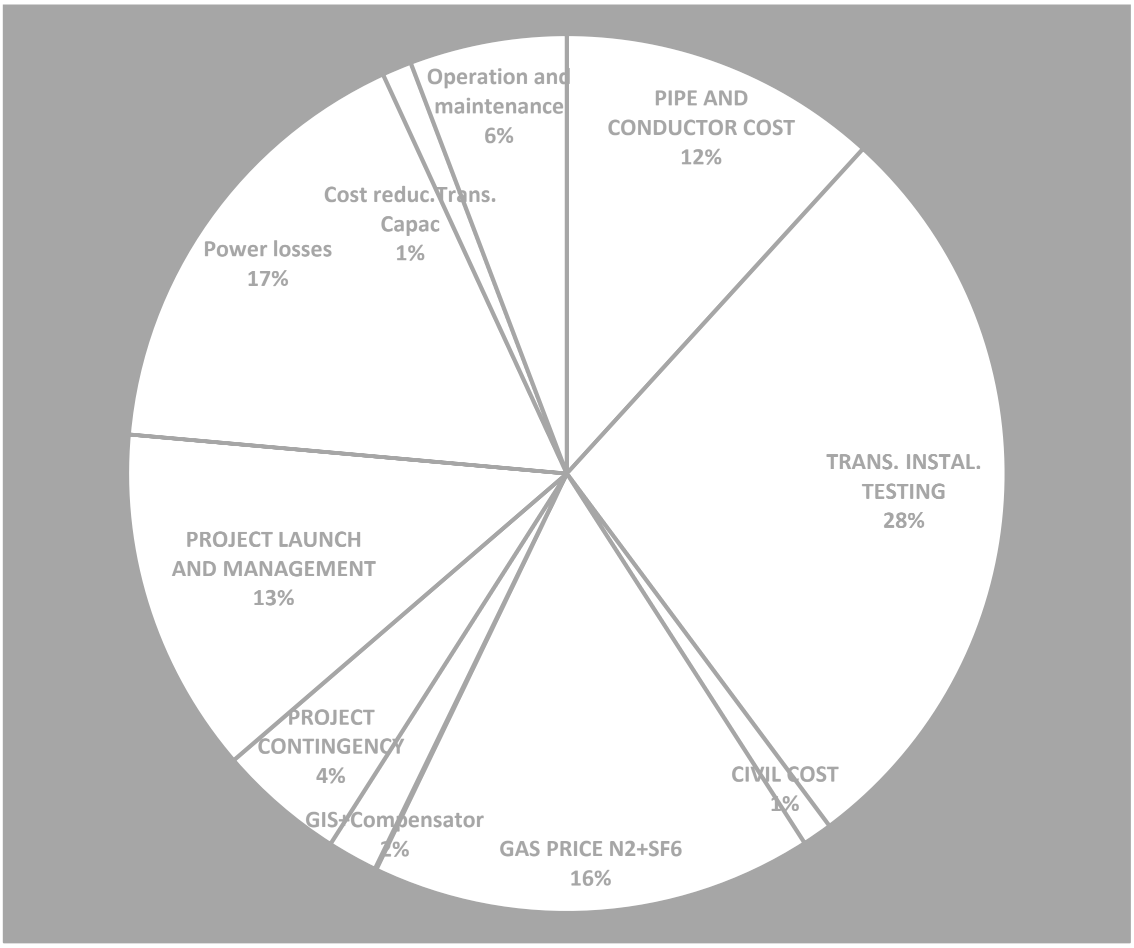

Figure 34. Total cost distribution.

4.1.2 Sensitivity study of GIL

The analysis of sensitivity shows the effect that different variables have on the final cost of the GIL infrastructure. In the previous graphic it can be seen that each cost does not have the same importance. Pipe and conductor cost and power losses are more significant than the others.

Normally in a sensitivity study of an installation the profitability study is done to come up with important economic variables as VAN and TIR or even Pay-Back time. However in this project, this parameters are not calculated as the inputs of money received due to operation and maintenance of the line are not available for a part of a bid grid. In case of GIL different arrangements have been done, to see which are the most important sensibilities that can have significant impact on the final price of the infrastructure.

4.1.2.1 Type of laying (soil: soft rock)

First of all, the civil work cost does not seem important in this project. In Table 30 it can be seen that the type of laying does have a little effect on the final cost. This cost ranges from 4,5 million for a directly buried to 34,5 million for squared tunnels.

Table 30. Type of laying sensitivity.

Civil works cost	Million €	€/m	€/MVA
Directly buried	5,6	59,0	2.296,2
Trench	27,9	293,7	11.429,9
Squared tunnel	41,2	433,6	16.873,3

4.1.2.2 Type of soil for a directly buried system

Secondly the type of soil is studied (Table 31). The columns refer to the same meaning as the previous study. It can be seen that independently of the type of soil civil works are still almost insignificant for the total cost referring to less of 2%.

Table 31. Type of soil sensitivity.

	Million €	€/m	€/MVA
Disaggregate	1,1	11,3	441,7
Loose	1,3	13,6	529,5
Compact	1,6	17,0	662,0
Hard	2,8	29,5	1.147,6
Soft rock	5,6	59,0	2.296,2
Hard rock	9,0	94,4	3.673,5

4.1.2.3 Total cost function of metal price

In this case study the price of metal is in reference to Table 25 4,2 €/kg for the outer enclosure pipes and 5,2 €/kg for the conductor pipes. As can be seen in the previous charts, the price of the pipes is one of the most significant components of the GIL installation, therefore, it is of huge interest to know the effect that the aluminium price has on the total cost.

In Table 32 can be appreciated as total cost of GIL infrastructure does highly depend on price of metal. This shows the great importance that have metal prices to try to reduce as much as possible installations price.

Table 32. Sensitivity study for the price of metal

Price of metal	Cost of metal parts (M€)	TOTAL COST (M€)	%
2€/kg	24,4	**426,6**	5,7
3€/kg	36,5	**459,1**	8,0
4€/kg	48,57	**491,6**	9,9
5€/kg	60,6	**524,1**	11,6

4.1.2.4 Gas mixture

The gas mixture used nowadays does have high environmental concerns due to the presence of SF_6. Since many years alternative gases have been studied to try to replace SF_6. Perhaps the insulating gas CF_3I can be the alternative in the near future. Techniques for producing this gas are being highly improved, therefore its price is being constantly reduced. Furthermore this new production methods may reach necessary requirements to ensure massive industrial production. In reference to [12] the price of CF_3I has been reduced over 630 £/kg to 62,86 £/kg in 2014. The change rate used between £ and € is 1,1 € is 1£.

The mass of gas required for 1 km single phase GIL is 5,72 tonnes, which makes 1.630 tonnes for the studied case, that is for a three phase system 95 km long [12]. With this information is made the sensitivity study for the alternative gas CF_3I. In Table 33 are shown values for total cost in reference to gas prices.

Table 33. Gas sensitivity

Price CF_3I [€/kg]	Total cost (M€)	Gas Price (M€)	%
69,15 (2014)	**575,4**	**112,7**	**19,6**
50	**490,1**	**81,5**	**16,6**
25	**380,4**	**40,8**	**10,7**
10	**314,6**	**16,3**	**5,2**
5	**292,7**	**8,2**	**2,3**

It can be seen that total price of the GIL infrastructure at 2014 prices is much more expensive than when SF_6 is used. This high price may make GIL not an appropriate alternative to be used. In case prices were reduced, probably the CF_3I gas would be the alternative.

4.2 Overhead lines

It is of high interest to compare total cost of investment and life-long expenses between GIL installations and OHL. This interest is motivated because, normally transmission system operators tend to select OHL installations instead of other systems such as underground lines or even GIL, due to their lower cost. The OHL will be compared to the GIL option for the presented case study. Furthermore in this case study it is especially important to see if there are any cheaper technologic solution to face environmental restrictions[32].

To study the costs of overhead and underground lines, the costs of installation have been obtained from [37][38]. This document presents costs associated to the construction and maintenance of transmission lines, i.e. OHL and underground cables, in Spain.

Regarding data for the construction of the OHL system defined by REE in [39] and [32] for the connection between Pinilla and Cofrentes, it is collected in Table 34.

Table 34. Project construction parameters.

System	Alternating three phase current
Voltage	400 kV
Conductor's maximum temperature	85 ºC
Number of circuits	2 (1 installed)
Number of conductors per phase	3
Type of conductor	Condor AW

Other important data referred to this project such as lifelong time, discount rate, working hours, etc, is the same as for the GIL installation.

4.2.1 Initial investment costs. Fixed costs

According to the information given for the initial investment costs in [37], price for the studied 400 kV line is 373.047 €/km. This cost refers to cables, structures, civil works, installation cost and even launch, management and contingency. Notice that the selected type of OHL project is 400 kV (triplex) simple circuit which refers to the installed circuit.

Apart from the distance dependent costs, the cost of GIS installed at each end of the infrastructure also have to be included. According to [34] each GIS for a 400 kV and 63 kA system is 2,5 M€.

Total initial investment costs are shown in Table 35:

Table 35. Total initial cost.

	Million €	€/m	€/MVA	€/year
Initial investment				
Distance dependent costs	35,4	373,0	14518,4	885986,6
Distance non-dependent costs	5,0	52,9	2058,6	125628,3
Total initial installation cost	**40,5**	**425,9**	**16577,1**	**1011614,9**

4.2.2 Variable costs

The variable costs of installation include the operation, maintenance, the cost of power losses and the cost related to a reduction of power capacity of the line due to reactive power.

4.2.2.1 Operation and maintenance

Costs for maintenance and operation are obtained from the reference [37]. It can be seen that the maintenance cost per year for a 400 kV line is 3.106 €/km.

In order to calculate the total cost for the life-long time of the installation (40 years) the following equation is used:

$$\mathrm{M\&O} = \frac{(1+\mathrm{i})^{\mathrm{n}}-1}{\mathrm{i}(1+\mathrm{i})^{\mathrm{n}}} * \ \mathrm{Cost}_{\mathrm{M\&O}} \quad (66)$$

where;

i: discount rate;

n: installation's number of years of life;

In the studied case M&O= 5,1 M€ for the lifetime period.

4.2.2.2 Power losses in cables and reduction of transmission energy due to reactive power

The study of the costs of these parameters seem important as they may have a great effect on total final cost of a high voltage line. In order to come up with these parameters, power losses and the capacitive and inductive power in the line, it is necessary to know the values of resistance (Ω) capacitance (F) and inductance (H).

The OHL conductor used in this project has been indicated at the project done by the company REE, for this specific new electric interconnection [38]. The main properties of the cable are indicated in product specifications tables as [40]. Note that the conductor used is Condor/AW which is formed by aluminium wires, concentrically stranded around a steel core wire. In Table 36 significant data has been collected [40]:

Table 36. Conductor's data.

Mass	1116,2 kg/km
Resistance	0,069 Ω/km
Total diameter	27,73 mm
Steel diameter (core)	9,24 mm
Aluminium cross section area	402,6 mm^2
Total cable section	603,48 mm^2

Note that the resistance per km has been indicated for a temperature of 25 ºC.

From [41], the relationship between resistance and temperature is:

$$\mathrm{R}_2 = \mathrm{R}_1\,[1 + \alpha(\mathrm{T}_2 - \mathrm{T}_1)] \qquad (59)$$

where;

$\mathrm{R_i}$: resistance at temperature ($\mathrm{T_i}$ [K]) [Ω];

α: temperature coefficient [1/K].

For aluminium the temperature coefficient is $4{,}46 * 10^{-3}$ [1/K] [42]; it is only considered the coefficient of temperature of aluminium as the great part of the conductor's section is made of aluminium.

The working temperature depends highly on many parameters, most of them uncontrollable; in order to give an approximation of the resistance at normal conditions, the temperature considered is 85ºC [38]. With this assumption, the resistance of each conductor in OHL is:

$$\mathrm{R}_2 = \mathrm{R}_1\,[1 + \alpha(\mathrm{T}_2 - \mathrm{T}_1)] = 0{,}069\,[1 + 4{,}46 * 10^{-3}(85 - 25)] = 0{,}087\ \Omega/\mathrm{km} \qquad (60)$$

Intensity per cable for the referred line which has one circuit and three conductors per phase is:

$$\mathrm{I} = \frac{\mathrm{S}}{3*\sqrt{3}*400} = \frac{2441}{3*\sqrt{3}*400} = 1{,}17\ \mathrm{kA} \qquad (61)$$

To calculate the inductance and capacitance parameters of the studied line, it is important to know their dependence on the geometry of the towers and the material of the conductor. In this case there is a beam of three conductors per phase collocated at the vertex of a regular polygon, in this case an equilateral triangle.

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The geometry and distances between conductors of a beam and the distances between phases of the system are shown in Figure 35.

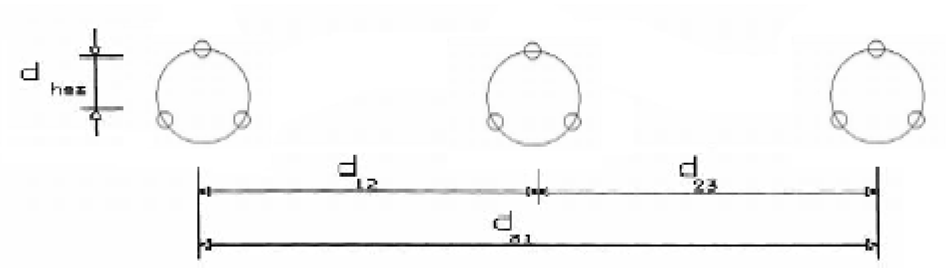

Figure 35. Distances for beams of conductors. (Data source: [37])

The type of tower and dimensions have been obtained from a similar project done by REE. In Figure 36 are indicated their dimensions. Notice that in the project Pinilla – Cofrentes, although the tower used can sustain two circuits, to date only one circuit has been installed [38], that means that only one of the symmetric parts is used.

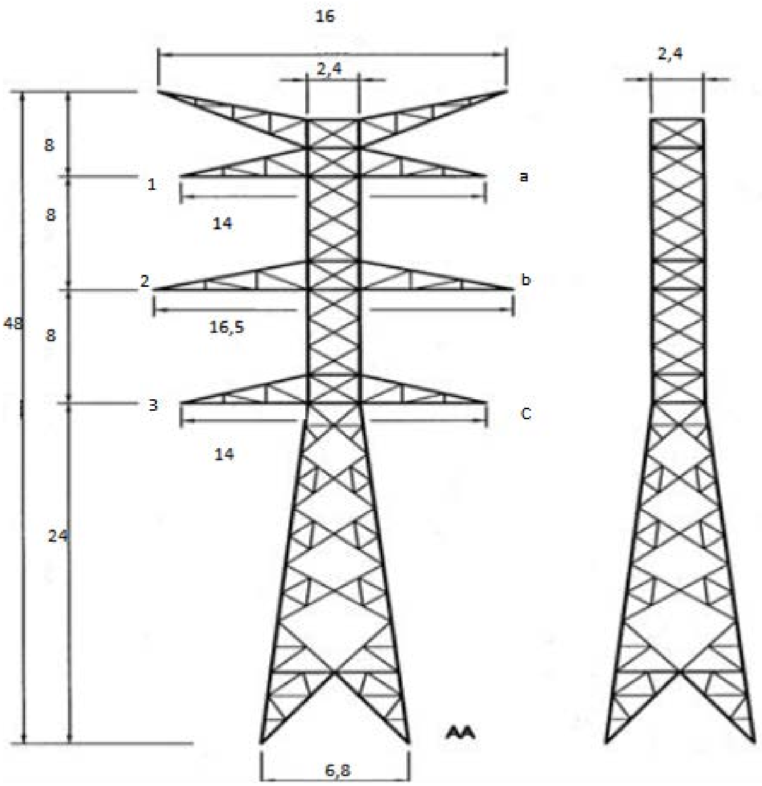

Figure 36. OHL tower. (Data source: [39])

The inductance per km is calculated [41]:

$$L = \ln\frac{DMG}{RMG} \quad [mH/km] \qquad (62)$$

The DMG (average geometric distance) parameter depends on the geometry of tower [41]:

$$\mathrm{DMG} = \sqrt[3]{\mathrm{DMG}_{12} * \mathrm{DMG}_{23} * \mathrm{DMG}_{31}} \quad (63)$$

A rigorous calculus of the DMG parameter has to consider all distances between conductors that form a beam and with all the different beams. But as distance between conductors of the same beam is much shorter than distance between beams, the parameter DGM can calculated approximately as [41]:

$$\mathrm{DMG} \cong \sqrt[3]{\mathrm{d}_{12}\mathrm{d}_{23}\mathrm{d}_{31}} \quad (64)$$

As all conductors of the line have got the same dimension and composition, the same number of conductors is installed in each beam and dimensions of the different beams are the same, the average geometric radius is calculated as [41]:

$$\mathrm{RMG} = \sqrt[\mathrm{n}]{0{,}779\ \mathrm{n}\ \mathrm{r}_{\mathrm{cond}}\mathrm{r}_{\mathrm{beam}}^{\mathrm{n}-1}} \quad (65)$$

where; $$\mathrm{r}_{\mathrm{beam}} = \frac{\mathrm{d}_{\mathrm{beam}}}{2\sin\left(\frac{\Pi}{\mathrm{n}}\right)} \quad (66)$$

In the designed beam, as there are three conductors per beam, distance between conductors is 300 mm and the beam's radius is 173,2 mm. Remember that the beam forms an equilateral triangle where on the vertex are situated the conductors. The conductor's radius is 13,81mm referred to the 600 mm^2. Note that all distances are expressed in mm.

where;

L: coefficient of mutual induction per km [H/km];

μ_0: magnetic permeability (μ=1 for aluminium-steel conductors);

DMG: average geometric distance between axis of phases [mm];

RMG: average geometric radius [mm];

n: number of conductors per phase= number conductors per beam;

$\mathrm{r}_{\mathrm{cond}}$: conductor's radius [mm];

$\mathrm{r}_{\mathrm{beam}}$: beam's radius [mm] (see Figure 40);

$\mathrm{d}_{\mathrm{beam}}$: distance between two conductors of the same beam [mm];

d_{ij} : distance between phases [mm] (see Figure 40).

Therefore value for the inductance parameter is:

$$L = \frac{\mu_0}{2\Pi} = \ln\frac{DMG}{RMG} = 2{,}32 \text{ mH/km} \qquad (67)$$

Regarding the capacitance of the line with three conductors per phase, this parameter can be calculated with the following equations [41]:

$$C = \frac{\mathcal{E}_0\, 2\Pi}{\ln(\frac{DMG}{R_{eq}})} \qquad (68)$$

$$DMG = \sqrt[3]{d_{12}d_{23}d_{31}} \qquad (69)$$

$$R_{eq} = \sqrt[n]{n r_{cond} r_{beam}^{n-1}} \qquad (70)$$

With the following equations it has been assumed the transposition between phases.

where;

C_k : capacitance [nF/km];

R_{eq}: equivalent radio [mm].

Therefore, the value for capacitance of the line is:

$$C = \frac{\mathcal{E}_0\, 2\Pi}{\ln(\frac{DMG}{R_{eq}})} = 2{,}49 * 10^{-8}\,\frac{F}{km} \qquad (71)$$

In Table 37 are shown values for resistance capacitance and inductance of the OHL line.

Table 37. RLC values for OHL.

Line Data	R [Ω/km]	L [mH/km]	C [μF/km]
	0,087	2,32	0,0249

With values obtained (ratio Q/P<0,2), no compensation units are needed; therefore there are no losses referred to the compensation units; however the cost of power capacity reduction due to reactive power has to be studied.

Table 38. Variable costs

	Million €	€/m	€/MVA	€/year
Power losses	191,1	2.011,7	78.292,4	4.777.794,4
Cost reduct.Trans. Capac	81,6	858,8	33.423,8	2.039.687,1
Total Maintenance and operation life-long cost	5,1	53,3	2.074,2	126.578,3
Losses in Compensation	0	0	0	0
Total variable costs	**277,8**	**2.923,8**	**113.790,4**	**6.944.059,8**

To sum up the total cost of an OHL line is:

Table 39. Total costs for OHL

	Million €	€/m	€/MVA	€/year
TOTAL COST	**318,2**	**3349,7**	**130.367,5**	**7.955.674,7**

4.3 Underground lines

It is of interest to compare total cost of investment and life-long expenses between GIL installations and underground installations. This interest is motivated because, both infrastructures may be similar in terms of civil works; therefore, it is important to know the differences in the cost components, especially in reference to power losses and reactive power consumption and generation, between underground lines and GIL installations is of high interest to introduce the less expensive solution. This comparison study is done for the line Pinilla-Cofrentes.

In reference to underground cables, they cannot use air as an insulator medium, therefore they need to provide their own insulation. In this case it is studied the XLPE cables which consist on the following components [43]:

- Conductor: copper or aluminium
- XLPE insulation
- Metallic screen
- Non-metallic outer sheath made of PE or PVC, etc.

As reported in [44], the IEC 62067 XDRCU-ALT 400/230 kV is the suitable cable to use in this 400 KV installation. The material for the conductor is copper. In order to decide the section it has been used the specification table [44] which relates voltage, current, type of laying and section. To calculate the section it is necessary to specify the current flowing per each conductor and the type of three-phase laying: trefoil or flat formation.

Intensity flowing through one conductor for a trefoil laying installation (see Figure 37, note that the trefoil laying installation consists of three-phase systems) is:

$$\mathrm{I} = \frac{\mathrm{S}}{\mathrm{n}*\sqrt{3}*400} = \frac{2441}{\mathrm{n}*\sqrt{3}*400} = 3{,}52\ \mathrm{kA} \qquad (72)$$

As for n=1 the maximum rated current for a cable is exceeded (maximum intensity is 1873 A [44]), two circuits are used.

$$\mathrm{I} = \frac{\mathrm{S}}{\mathrm{n}*\sqrt{3}*400} = \frac{2441}{\mathrm{n}*\sqrt{3}*400} = 1{,}76\mathrm{kA} \qquad (73)$$

where;

n: number of conductors per phase: n=2.

The number of conductors per phase (n=2) has been decided in reference to the maximum intensity that can flow through a conductor. The same criteria is used to select the section for the conductor: 2.500 mm^2 [44]. Main data of the underground installation is shown in Table 40:

Table 40. Underground Cable installation's data

System	Alternating three phase current
Voltage	400 kV
Cable	IEC 62067 XDRCU-ALT 400/230kV
Number of circuits	1
Number of conductors per phase	2
Type of laying	Trefoil (see Figure 37)
Section of conductor	2.500 mm^2
Conductor's material	Copper

The other main data referred to this project is the same as for the GIL installation.

4.3.1 Initial investment cost

In the reference [37], have been found the regulated prices for HVAC electric underground cable installations in Spain. On the one hand, the unitary values for investment in underground cable systems for a double cupper circuit of 2.500 mm^2 of section is 5.110.149 €/km. On the other hand the cost related to the protection systems (GIS) of the installation are for a 400 kV, 63 kA system 2.512.565 € per GIS, that means two units used, 5.025.130 € for the designed infrastructure.

Table 41. Initial investment cost

	Million €	€/m	€/MVA	€/year
Distance dependent costs	485,5	5.110,5	198.893,9	12.137.500,0
Distance non-dependent costs	5,0	52,9	2.058,6	125.628,3
Total initial installation cost	**490,5**	**5.163,4**	**200.952,5**	**12.263.128,3**

4.3.2 Variable costs

4.3.2.1 Operation and maintenance

Costs for maintenance and operation are obtained from the reference [37]. It can be seen that the maintenance cost per year for a 400 kV for a multiple circuit line is 3.417 €/km.

In order to calculate the total cost for the life-long time of the installation (40 years) the following equation is used:

$$\mathrm{M\&O} = \frac{(1+i)^n-1}{i(1+i)^n} * \mathrm{Cost}_{\mathrm{M\&O}} \quad (74)$$

4.3.2.2 Power losses in cables and reduction of transmission energy due to reactive power

In reference to power losses due to resistance of the cable, as the conductor is made from cupper, from [43] it can be seen that for a copper section of 2.500 mm^2 the resistance per km at 25ºC is: 0,0072 Ω/km. From [41], resistance at working temperature is calculated with the temperature coefficient of copper which is $3{,}9 * 10^{-3}$ [1/K] [42].

As in the case of conductors in OHL, the working temperature depends highly on uncontrolled parameters. In order to give an approximation of the resistance it is supposed a constant temperature of 85ºC. With the following equation is calculated the resistance parameter of the line [41]:

$$\mathrm{R}_2 = \mathrm{R}_1\,[1+\alpha(\mathrm{T}_2-\mathrm{T}_1)] = 0{,}0072 * [1+3{,}9*10^{-3}(65-25)] = 0{,}00832\ \Omega/\mathrm{km} \quad (75)$$

The capacitance of the high voltage conductor depends on the type of insulator and its geometry. As the cable can be approximated to a homogenous cylinder, its field is represented to a radial field cable. The capacitance parameter is calculated with [43]:

$$\mathrm{C} = \frac{\varepsilon_r}{18*\ln\left(\frac{D}{d}\right)} \quad (76)$$

The value for D is 136 mm and d=56,4mm [44].

where;

C: capacitance [µF/km];

ε_r: relative permittivity (XLPE: 2,5 [43]);

D: diameter of the main insulation, diameter of the cable [mm];

d: diameter of the conductor [mm].

The inductance depends on the relation between the conductor axis spacing and the external conductor diameter. In this case a trefoil laying configuration is chosen as shown in Figure 37:

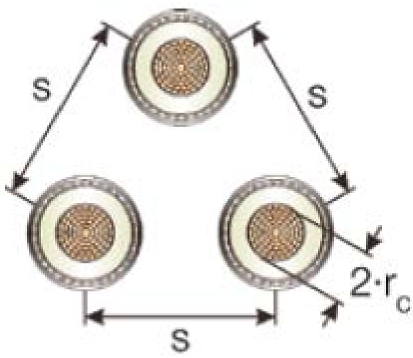

Figure 37. Trefoil cable configuration. (Data source:[39]).

The operating inductance for all three cables is calculated as [43]:

$$\mathrm{L} = 0{,}05 + 0{,}2 * \ln\left(\frac{k*s}{r_c}\right) \quad (77) \quad [\mathrm{mH/km}]$$

where;

k=1 for a trefoil formation [43];

r_c: conductor radius [mm];

s: distance between radius [mm]

The resistance, capacitance and inductance parameters of the underground cable installation result to be:

Table 42. RLC values

Line Data	R [Ω/km]	L [mH/km]	C [μF/km]
	0,00832	0,35	0,23

With values obtained (ratio Q/P<0.2), no compensation units are needed; therefore there are no losses referred to the compensation units; however the cost of power capacity reduction due to reactive power has to be studied. In Table 43 are shown the variable costs for the Underground Cable installation. It is remarkable to outline the low prices for power losses; this low rates are a consequence of the low resistance values found for the cables used in this installation.

Table 43. Variable costs

	Million €	€/m	€/MVA	€/year
Power losses	27,9	293,3	11.415,7	696.643,5
Cost reduct.Trans. Capac	8,3	87,4	3.400,9	207.541,0
Losses in Compensation	0,0	0,0	0,0	0,0
Total variable costs	**36,2**	**380,7**	**14.816,6**	**904.184,6**

Table 44. Total cost

	Million €	€/m	€/MVA	€/year
TOTAL COST	**526,7**	**5.544,1**	**215.769,2**	**13.167.312,8**

4.4 Case study results discussion

From the comparison study for the Pinilla-Ayora-Cofrentes electric line has been done a cost approximation for three different electric technologies. These cost approximations are of high interest for national grid companies as both the differences between the cost components can be outlined and total costs of lines can be predicted. Prices got for this installation comparison can be extrapolated to other similar installations.

In reference to the case study done, it can be seen that as it was predicted GIL installations may have more expensive cost rates than OHL; furthermore, in this case the costs associated to GIL and Underground Cable installations, are very similar. This similarity between prices of both technologies can be explained by the higher capacity of GIL to flow greater quantities of current [45].

Notice that this competitiveness in price between Underground Cable installations and GIL depends much on the significant sensible cost parameter as it is the metal price; in Table 45 is given a sum up of all the main cost components of each studied technology for the case of the new installation Pinilla – Cofrentes. Different metal price scenarios can be seen to realize when would be a GIL installation cheaper than other types of technologies depending on this sensitivity; also are shown different price scenarios for the gas CF_3I which may be the future of GIL installations.

Table 45. Cost comparison GIL OHL and Underground cables.

GIL		**Million €**
	Initial investment	**388,2**
	Variable costs	**120,8**
	Total cost	**509,0**
GIL sensitivity		
Price of metal		**Total cost**
2 €/kg		**426,6**
3 €/kg		**459,1**
4 €/kg		**491,6**
5 €/kg		**524,1**
Price of gas (CF_3I)		**Total cost**
5 €/kg		**292,7**
10 €/kg		**314,6**
25 €/kg		**380,4**
50 €/kg		**490,1**
69,15 €/kg (2014)		**575,4**
OHL		
	Initial investment	**40,5**
	Variable costs	**277,8**
	Total cost	**318,2**
Underground Cables		
	Initial investment	**490,5**
	Variable costs	**36,2**
	Total cost	**526,7**

This previous table and the cost study done can provide some conclusions:

- The price sensitivity shows how much is important the metal price and the gas price in order to ensure GIL to be an alternative to be implemented in HVAC installations, at least in comparison with underground cable installations.
- Regarding variable costs, it is significant that there can be seen big differences in the power losses cost and the cost due to reduction of power capacity as a cause of the variation of the resistance, inductance and capacitance parameters for the different technologies. Note that this differences in cost range from 36,2 million **€** for an Underground Cable installation to 277,8 million **€** for an Overhead Line. Note the low variable costs for underground installations, which are a mainly a consequence of the low resistance values for the cable used.
- The variable costs of OHL installations are huge due to high power losses, mainly a consequence of the high resistance value of the conductor. This can be contrasted with low initial investment, which is to lowest in reference to GIL and Underground Cables.

In the end it can be said that GIL can become a competitive solution in comparison to OHL and Underground Cables in many cases if metal and gas prices are low enough that ensure GIL competitiveness.

5. Conclusion

Finally with the developed tool it is possible for institutions and electric companies to do a cost study of the GIL technology. Of course, this tool is going to enease the GIL implementation, as a cost study gives the opportunity to compare technologies with economic parameters.

Furthermore, it can be stated that GIL is not so far away from being a more used HVAC electric system; this is because on the one hand electric interconnections will need to have higher power rates at competitive prices, and this is an advantage for GIL; on the other hand the great visual and environmental impact that create OHL is willing to be defeated; it can be done by using the underground layout for GIL.

With this thesis and tool, the opportunity to design and see the cost for different installation arrangements is possible, therefore it may become simpler the possibility of studying which are those optimum technical solutions that come with the best environmental arrangement.

In the end, this work has provided some cost functions that were previously not found in the literature. Therefore, the aim of this final degree projects is considered to be accomplished, having provided a tool which gives a cost approximation of all technical arrangements of GIL transmission system.

On the other hand, some future work is able to be done to expand the utility of the technical-economic analysis of GIL:

- Perhaps the most interesting one would be to give a complete tool that would give at the same time a cost approximation for the main electric transmission technologies (OHL and Underground Cables) with GIL.
- Another point that can be improved, technical values for GIL do not only depend on voltage and apparent power, but they depend on many other aspects as working temperature; it would be of high interest to come up with an improved tool that takes into account other parameters not used to approximate cost.
- The next step for the designed tool is the possibility for it to get from the internet current and updated values for the material prices.

References

[1] "Gas Insulated Transmission Lines." [Online]. Available: http://www.betaengineering.com/high-voltage-industry-blog/gas-insulated-transmission-lines. [Accessed: 07-Jun-2018].

[2] "Paquete de medidas sobre clima y energía hasta 2020 | Acción por el Clima." [Online]. Available: https://ec.europa.eu/clima/policies/strategies/2020_es. [Accessed: 07-Jun-2018].

[3] "Electricity interconnection targets - European Commission." [Online]. Available: https://ec.europa.eu/energy/en/topics/infrastructure/projects-common-interest/electricity-interconnection-targets. [Accessed: 06-Jun-2018].

[4] H. Koch, "Gas-Insulated Transmission Lines (GIL)," *Gas-Insulated Transm. Lines*, 2011.

[5] E. Ten and Y. Statement, "Appendix E," 2015.

[6] "torres eléctricas alta tensión - Buscar con Google." [Online]. Available: https://www.google.com/search?q=torres+eléctricas+alta+tensión&client=firefox-b-ab&tbm=isch&tbo=u&source=univ&sa=X&ved=0ahUKEwjXoLm15dDbAhUIvBQKHV8vBpwQsAQIOQ&biw=1366&bih=641#imgrc=tKFaTKCDvBrzdM: [Accessed: 13-Jun-2018].

[7] M. Rafiq, D. Khan, M. Rafiq, S. F. Rafique, I. Khan, and F. Abbas, "Comparison of transmission losses and voltage drops of GIL (Gas Insulated transmission line) and overhead trans .... Comparison of transmission losses and voltage drops of GIL (Gas Insulated transmission line) and overhead transmission lines," no. April, pp. 4–7, 2017.

[8] E. Network, "Technologies for Transmission System," 2016.

[9] "Gas-insulated transmission lines (GIL)."

[10] "California Limits SF6, World's Most Potent Greenhouse Gas." [Online]. Available: http://www.ens-newswire.com/ens/mar2010/2010-03-02-091.html. [Accessed: 21-Feb-2018].

[11] H. Koch, *Gas-Insulated Transmission Lines*. .

[12] K. Elnaddab, "Evaluation of Gas Insulated Lines (GIL) for Long Distance HVAC Power Transfer," no. December, 2014.

[13] D. M. It, *Fa act tors s fo or In nve estm me ent De ecis sion n L vs . v C Ca ble es for r AC C Tra T ans mis ssio on*, no. December. 2015.

[14] "Construction of First Gas Insulated Transmission Line in Japan," p. 500, 1975.

[15] U. N. E. Afnor, "ALUMINIUMS General Tables Equivalences," pp. 10–11.

[16] C. Westboro, “Compressed Gas Insulated Transmission Bus Systems,” no. 508, pp. 1–27.

[17] I. B. Corral, “No Title,” 2018.

[18] “5052 aluminium alloy - Wikipedia.” [Online]. Available: https://en.wikipedia.org/wiki/5052_aluminium_alloy. [Accessed: 15-Mar-2018].

[19] C. Westboro, “Compressed Gas Insulated Transmission Bus Systems Proven Solutions.”

[20] *Aluminium Alloys - Aluminium 6063/6063A Properties, Fabrication and Applications*. 2005.

[21] “Banco de Precios.” [Online]. Available: http://www.construinfo.com/FICHAP.ASP?CODIGO1=&CODIGO2=01TZ. [Accessed: 14-Mar-2018].

[22] R. Benato, C. Di Mario, and H. Koch, “High capability applications of long gas-insulated lines in structures,” *Proc. IEEE Power Eng. Soc. Transm. Distrib. Conf.*, vol. 35131, pp. 605–612, 2006.

[23] P. Sheet, P.-E. February, C. Price, and S. Ph-, “price list and condensed catalog,” 2012.

[24] J. Yli-hannuksela, “THE TRANSMISSION LINE COST,” 2011.

[25] “Precio en España de m^2 de Fachada pesada de placa alveolar de hormigón pretensado. Generador de precios de la construcción. CYPE Ingenieros, S.A.” [Online]. Available: http://www.generadordeprecios.info/obra_nueva/Fachadas/Pesadas/Paneles_prefabricados_de_hormigon/FPP030_Fachada_pesada_de_placa_alveolar_de.html. [Accessed: 15-Mar-2018].

[26] “Issued 31st January 2012 With errata April 2012,” no. January, 2012.

[27] “Predicción del coste de la obra civil de un túnel ejecutado por métodos convencionales según Subterra Ingeniería - Obras Urbanas.” [Online]. Available: https://www.obrasurbanas.es/prediccion-del-coste-de-la-obra-civil-de-un-tunel-ejecutado-por-metodos-convencionales-segun-subterra-ingenieria/. [Accessed: 14-Mar-2018].

[28] L. Chen, P. Widger, M. S. Kamarudin, H. Griffiths, and A. Haddad, “CF3I Gas Mixtures: Breakdown Characteristics and Potential for Electrical Insulation,” *IEEE Trans. Power Deliv.*, vol. 32, no. 2, pp. 1089–1097, 2017.

[29] *SF6 (Hexafluoruro de azufre)*. .

[30] J. Rebled Lluch, “Power transmission systems for offshore wind farms: Technical-economic analysis,” pp. 1–121, 2015.

[31] P. G. T. M. M. Gcb, “Gas Insulated Switchgear (GIS) General Presentation Estimated Total Market Size 2016,” 2016.

[32] D. E. L. A. Línea and A. Eléctrica, “ESTUDIO DE IMPACTO AMBIENTAL DE LA LÍNEA ELÉCTRICA A

400 kV PINILLA-CAMPANARIO-AYORA-COFRENTES.," 2008.

[33] "China tubo del aluminio 5052, tubo redondo sacado, inconsútil para la fabricación del buque encendido Global Sources." [Online]. Available: http://spanish.globalsources.com/gsol/I/Aluminum-pipe/p/sm/1152696538.htm#1152696538. [Accessed: 14-Jun-2018].

[34] "China molino 6061 que acaba los tubos de aluminio del color natural con grueso de pared fino y el OD en la promoción encendido Global Sources." [Online]. Available: http://spanish.globalsources.com/gsol/I/Aluminum-pipe/p/sm/1142760038.htm#1142760038. [Accessed: 14-Jun-2018].

[35] "Purchase SF6 Gas from Concorde Specialty Gases | Concorde Specialty Gases." [Online]. Available: http://www.concordegas.com/purchase-sf6-gas/. [Accessed: 14-Jun-2018].

[36] "Liquefied Nitrogen Ln2 Gas Cylinder - Buy Liquefied Nitrogen Cylinder,Ln2 Gas Cylinder,Nitrogen Gas Cylinders Product on Alibaba.com." [Online]. Available: https://www.alibaba.com/product-detail/liquefied-nitrogen-LN2-gas-cylinder_60744083702.html?spm=a2700.7724857.normalList.2.70916c21aAio9B&s=p. [Accessed: 14-Jun-2018].

[37] M. De Industria and E. Turismo, "Orden IET / 2659 / 2015 , de 11 de diciembre , por la que se aprueban las instalaciones tipo y los valores unitarios de referencia de inversión y de operación y mantenimiento por elemento de inmovilizado que se emplearán en el cálculo de la retribución de," pp. 1–16, 2015.

[38] M. D. E. Industria and E. Y. Turismo, "Boletín oficial del estado," pp. 45805–45808, 2015.

[39] "Planificación de la red de transporte de electricidad 2015-2020 - Comunidad," 2015.

[40] A. Aplicaciones, N. Ntc, A. B-, and A. B-, "ACSR / AW ACSR / AW CA tal y p," pp. 109–115.

[41] A. Sumper, "Sistemas El ´," 2017.

[42] R. M. Mujal Rosas, *Cálculo de líneas y redes eléctricas*. 2002.

[43] X. Land and C. Systems, "XLPE Land Cable Systems User ´ s Guide CONTENT."

[44] "HIGH VOLTAGE XLPE CABLE SYSTEMS Technical User Guide."

[45] G. Schöffner, K. Oswald, S. Ag, and H. Ptd, "INVESTMENT REDUCTIONS."